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The Pleistocene of the Mendip region : Aspects of the absolute dated, faunal and sediment records.

THE PLEISTOCENE OF THE MENDIP REGION : ASPECTS OF THE ABSOLUTE DATED, FAUNAL AND SEDIMENT RECORDS

By

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ABSTRACT AND SUMMARY

The Mendip Hills are approximately 35km south west of Bristol, in south west England. They are the most intensively studied karst area in Britain and there has been scientific interest in their Quaternary deposits for over 200 years.

This thesis aims to analyse the three major Pleistocene records of the Mendip region, which are:

1) the absolute dated record (eg uranium-series dated speleothems),

2) the faunal record (predominantly from cave sites), and

3) the cave sediment record (mainly at Westbury-sub-Mendip).

The presence of speleothems in Britain is indicative of warm, vegetated environments. Data from uranium-series determinations are analysed using the technique of Gordon & Smart (1984), and the presence and ages of 3 Upper Pleistocene interglacials (the 'Ipswichian Complex') and 6 interstadials are determined. Active speleothem growth in the UK is shown to have occurred simultaneously with:

1) high sea levels in the tropics, as indicated from uranium-series dated fossil corals.

2) Milankovitch insolation peaks,

3) interglacial beach formation in the Mediterranean (dated by Fission tracks), and

4) warm sea surface temperatures in the Atlantic (deep sea core data).

The speleothem record is shown to provide the best available absolute stratigraphic framework within which to interpret Upper Pleistocene deposits in Britain.

The fossil vertebrate data from the Mendip region sites is analysed by cluster techniques. It is compared with the records from the rest of Britain and a mammalian biostratigraphy is proposed in which at least 14 distinct faunas are recognised. The palaeoecology of some of these faunas is examined.

The problems of cave sedimentology are discussed and the utility of a number of laboratory techniques is examined. The climatic interpretations of cave deposits are considered, with particular reference to the Lower and Middle Pleistocene record at Westbury-sub-Mendip.

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AUTHOR'S DECLARATION

All the work in this thesis is the author's own except where otherwise stated. It has not previously been submitted as part of a degree requirement.

David Gordon
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CHAPTER I

INTRODUCTION

The Mendip Hills are approximately 35km south-west of Bristol in the south-west of England. They stretch from Brean Down in the west to Frome in the east (approximately 40km) and are less than 10km wide. They are formed by a series of Variscan periclines which have been eroded in places exposing the Old Red Sandstone and Lower Limestone Shale core, which is flanked by a complex sequence of Lower Carboniferous limestone, thus forming the smallest but most intensively studied karst area in Britain (and possibly the world). There has been active scientific interest in the Quaternary of the Mendip region for over 200 years and a vast body of literature now exists (see Hawkins & Tratman 1977). The reasons for this are three-fold:

1) The Mendip hills lie within easy reach of important trading centres and major urban areas, eg Bristol in this century, and Bath and Wells in previous centuries.

2) The Mendips lie to the south of the maximum extension of glacial ice during the last glaciation, and possibly of all of the Pleistocene glaciations (Bowen *et al* 1986); therefore Quaternary deposits have not been stripped by recent glacial erosion.

3) The highly karstified nature of the Mendip hills provides a large number of abandoned caves which have acted as sediment traps. Long Quaternary sedimentary sequences are preserved at several sites and the buffering effect of caves on climatic variation frequently leads to excellent states of preservation.

Therefore, unsurprisingly, a large number of sites of Quaternary interest are known from this small region (an initial literature survey identified 287 different sites). Many of these sites were excavated during the 19th and early 20th centuries and although a lot of information and facts are known about the Pleistocene in the Mendip region, very little analysis has been undertaken on this massive data source. Therein lies the rationale behind this thesis which is based upon the assumption that a greater amount of useful knowledge can be obtained by developing methods of analysing this huge data set than can be gained from discovering and excavating the 288th Mendip site. This approach requires further justification since it differs from the majority of UK theses concerned with the Pleistocene, which generally set out to gather new facts by discovering new sites and/or excavating old ones.

In 1983 Professor Richard West (arguably the greatest living British authority on the Quaternary) delivered a lecture at Cambridge on the 'status of Quaternary research in Britain' in which he noted that Quaternary studies had not yet found their 'Newton', and that despite the fact that almost as much was known about the Quaternary period than about the rest of the geological column put together, the theoretical base of this knowledge was slim. He concluded that the answer lay in discovering new sites and better stratigraphy. The author considers this to be essentially a 'Baconian' argument and critically flawed. While the discovery of new sites and better stratigraphy are undoubtedly desirable, it seems unlikely that they alone will solve the major problems of Quaternary science. Work in many branches of the philosophy of science has demonstrated that integration, synthesis and theory can rarely be built up from the collecting, collating and arrangement of 'hard' facts (for example see Anon 1981). The inductive idea of science that correct theories will somehow 'bubble' to the surface once enough pure facts have been generated, is untenable. Scientific advancement comes from the development of theories that can then be tested by the facts and not the other way around. Although the majority of Quaternary researchers would probably agree with these sentiments, much of the practice of Quaternary studies is in the collection of new facts rather than in their analysis or the development of new theories. This is also true in the Mendip region where much of the source data has received little critical attention beyond that of the original authors. This thesis is an attempt to redress this balance. It sets out to do four things:

1) identify what knowledge it is possible to obtain about the past from the various Mendip Pleistocene records;

2) define the assumptions that this knowledge is based upon;

3) examine the theoretical and stratigraphic frameworks within which Pleistocene data can be interpreted;

4) develop analytical techniques for the interpretation of Pleistocene data.

During the course of this research many of the Mendip region sites discussed were visited and samples collected and analysed. However, no site reports are presented, and where new information resulting from these analyses is introduced it is for illustrative purposes and generally incidental to the main argument. Specific sites reports where warranted will be published elsewhere.

Quaternary research in the Mendip region has been mainly concentrated into three areas which form the basis of the major sections of this work. These are:

1) the absolutely dated record (Chapters II to IV);

2) the faunal record (Chapters V to VII), and

3) the sediment record (Chapters VIII and IX).

Different kinds of palaeoenvironmental information can be obtained from these three records and different forms of analysis are applicable to them. Therefore the three sections have been written as self-contained units; however where the records are complementary, attempts have been made at integration. One ultimate aim of Mendip Pleistocene studies would be the integration and synthesis of these three records, but this is not yet possible.

Finally this thesis takes an unashamedly global outlook, since the major Pleistocene climatic fluctuations were global in scale and not parochial events confined to the Mendip region. Therefore attempts are made, where relevant, to compare the Mendip region records with those from other regions of the UK and the world.

S E C T I O N I

THE ABSOLUTE DATED RECORD

CHAPTER II

POTENTIAL AND PROBLEMS OF THE SPELEOTHEM RECORD

Controls on Secondary Calcite Deposition

The potential for using speleothem, tufa and travertine deposits as palaeoclimatic indicators has long been recognised. (Franke 1965, Wells 1971.) The formation of these deposits is virtually exclusively associated with biological activity and therefore their presence is indicative of conditions favourable to life (eg primarily warm and wet environments).

Speleothems are secondary mineral deposits such as calcite stalagmites, stalactites and flowstones, which grow in limestone caves. The formation of calcite speleothems results from the production of CO_2 in the overlying soil by root respiration and microbial activity. Under favourable growth conditions soil atmosphere PCO_2's (partial pressure of carbon dioxide) can become elevated by several orders of magnitude compared to atmospheric PCO_2 (Pitman 1978). Percolating seepage-water will absorb CO_2 from the soil atmosphere and become aggressive and thus able to dissolve increased amounts of limestone or calcium bicarbonate. However, on contact with a cave atmosphere outgassing of CO_2 will occur since cave air PCO_2 levels are usually similar to atmospheric levels (Ek & Gewelt 1985). This loss of CO_2 causes an increase in pH, and the calcium dissolved in solution will precipitate as calcium carbonate (Ca Co_3) to form speleothems.

Travertine deposition is usually controlled by CO_2 from bicarbonate spring-mound waters, and hence deposition of calcium carbonate (Pentecost 1978, 1981). Large scale tufa deposition in Britain is associated with open forested environment during warm interglacial climates (Preece 1978). Maximum tufa deposition rates in the Mendips during the Flandrian occurred in the warmest stages of the interglacial (molluscan biozones C and D), although limited deposition had started earlier (molluscan biozones A and B) (Willing 1986). This pattern has been found in Flandrian sites in Wales and Dorset and in Hoxnian tufas in Hertfordshire and East Anglia (Preece 1978, 1980, Kerney *et al* 1980).

Although non-biogenic formation mechanisms are known for all these secondary calcite deposits, they can be considered as 'exceptions that prove the rule'. For example, speleothems can be deposited by evaporation, temperature differences and supersaturation due to dissolution of other calcium bearing minerals (common ion effect) (Thraillkill 1971, Dreybrodt 1982, Atkinson 1983). However, the number of speleothems in Britain known to have been formed by these non-biogenic mechanisms is extremely small.

Biological activity is determined by a large number of factors such as substrate conditions, nutrient availability, pH, pest abundance, predation, competition, etc. However, the primary controlling factors are usually temperature and water availability. The rate of all biological reactions is governed by temperature such that a 10°C increaso in temperature results in an approximate doubling in reaction speed, ie Q_{10} =2 (Sutcliffe 1977). Water is by far the most abundant component of all organisms since it provides the medium in which all biochemical reactions occur. Although the effects of low temperature and water scarcity are ameliorated by some arctic flora through modifications to biochemical pathways, eg C_4 photosynthesis,the overall effect on production is strictly limited (Sutcliffe 1977). It is therefore not surprising that the results of biological production such as soil and water PCO_2 levels vary on a global scale directly with mean annual temperature (Drake & Wigley 1979, Drake 1980) and water availability, as measured by actual evotranspiration (Brook *et al* 1983). Although soil temperature and water availability generally display a high inverse correlation, multifactorial studies have demonstrated that temperature is often of prime importance (Tamm & Krzysch 1963, Van Cleve & Sprague 1971). In mature forest soils 50% of CO2 production is due to root respiration (Nakane & Kira 1978, Nakane *et al* 1983), the rate of which is largely controlled by temperature since tap roots will buffer the effects of short periods of soil water deficit. However, CO_2 production from heterotrophic organic matter degradation is largely controlled by fungi and actinomyces numbers, which are strongly influenced by the soil moisture levels (Hudson 1977; Rai & Srivastava 1981). In a global study of mean growing season soil PCO_2 levels, a stronger relationship was found with mean annual actual evotranspiration than mean annual temperature (Brook *et al* 1983). However this work has been criticised for failing to control for the effects of vegetation type, which has been shown to significantly affect soil PCO_2 levels (Gunn 1984). Forest and woodland ecosystems would be expected to have higher soil PCO_2 levels than shrub or grassland due to their greater root biomass. This has been demonstrated under a range of temperate climatic conditions in New Zealand where soil PCO_2 levels were found to be higher under forest than under adjacent grassland during most of the year (Gunn & Trudgill 1982).

It is evident that under cold climatic conditions the formation of secondary calcite deposits will be extremely restricted due to reduced biological activity. Furthermore, periods of glacierization and the formation of continuous permafrost will greatly reduce infiltration rates and karst circulation. There is considerable confusion on this matter since many researchers have noted conduit flow in present day arctic areas. (P. Worsley *per comm*). However, these talies are invariably the result of concentrated recharge rather than diffuse recharge (Tolstikhin *et al* 1963, Kane & Stein 1984). The PCO_2 levels of concentrated recharge waters are generally similar to normal atmospheric values and they therefore rarely give rise to secondary calcite deposition. This argument is supported by the observation that speleothem volume is relatively small in present day arctic and alpine areas, compared to temperate regions where growth is often extensive; and tropical regions where massive accumulations of speleothem occur.

Statistical Analysis of $^{234}U/^{230}Th$ Dated Speleothems

The statistical analysis of the large number of U^{234}/Th^{230} dated sections of speleothem can provide valuable information of Quaternary interest, since it should be possible to determine the periods when active speleothem deposition was occurring, even if the rate of this deposition remains unknown. In order to do this three assumptions must hold true: firstly all the analyses must come from a region small enough to be relatively climatically homogenous; secondly there is no significant bias in the sample collection; and thirdly the sample size is sufficiently large to be representative.

Five hundred and twenty $^{234}U/^{230}Th$ analyses are available for study from the UK, five hundred and seventeen of which are from speleothem calcite and three from tufa in the lower channel at Marsworth. For this sample the three assumptions are probably valid. Although climatic gradients exist between Scotland and the Channel Islands, the amount of climatic variation is small compared to the magnitude of the climatic changes that have occurred during the upper Pleistocene. For the purpose of studying large scale climatic changes the UK can reasonably be considered to be climatically homogenous.

The problem of sample bias in the record is more serious. The majority of uranium series analyses have been carried out on speleothems of geomorphological interest, so there is no apparent bias towards sites with ages of particular Quaternary interest. This is not true in several European countries such as Hungary, Israel and France where speleothem dating has been more concentrated on archaeological sites (eg Schwarcz *et al* 1979, 1980; Schwarcz & Shoflek 1982; Schwarcz & Blackwell 1983; Schwarcz & Latham 1984). However, there is a potential systematic bias in the data towards younger material, since older speleothems are more likely to have been buried by sediments or removed by erosion. The effect of this bias is counteracted by the fact that most researchers are more interested in the older speleothems than the overtly younger material, since the older speleothems tend to be of greater geomorphological/geological importance and are therefore actively collected in preference to the younger formations. A quantification of the magnitude of these biasing factors is a non-trivial mathematical problem and has not been attempted in this study.

The problems associated with sample size in the analysis of radiometric dates have only been given serious consideration in the past decade. Shennan (1978) has demonstrated the sensitivity of fixed interval histograms to small sample sizes. The production of histograms using random numbers can produce similar frequency peaks to those calculated from radiometric age data (Shennan 1978; Hennig *et al* 1983). False peaks are most problematic with histograms containing fewer than 100 dates. Smoothing techniques such as the calculation of running means by combining dates from adjacent class intervals help to mitigate the effects of random clumping, but resolution becomes problematic with both real and statistical gaps being smoothed out equally. Geyh (1980) has shown that the relationship between resolution and the number of dates per class interval is:

$$s = \pm 1 / \sqrt{z}$$

$$= \pm \sqrt{T/(2 * Z * \sigma)}$$

where s = the relative statistical fluctuation in %

z = the population density, ie the number of dates per class interval, where the interval width is twice the standard deviation of the dates.

T = the time span.

Z = the number of dates within T

σ = the standard deviation of the dates.

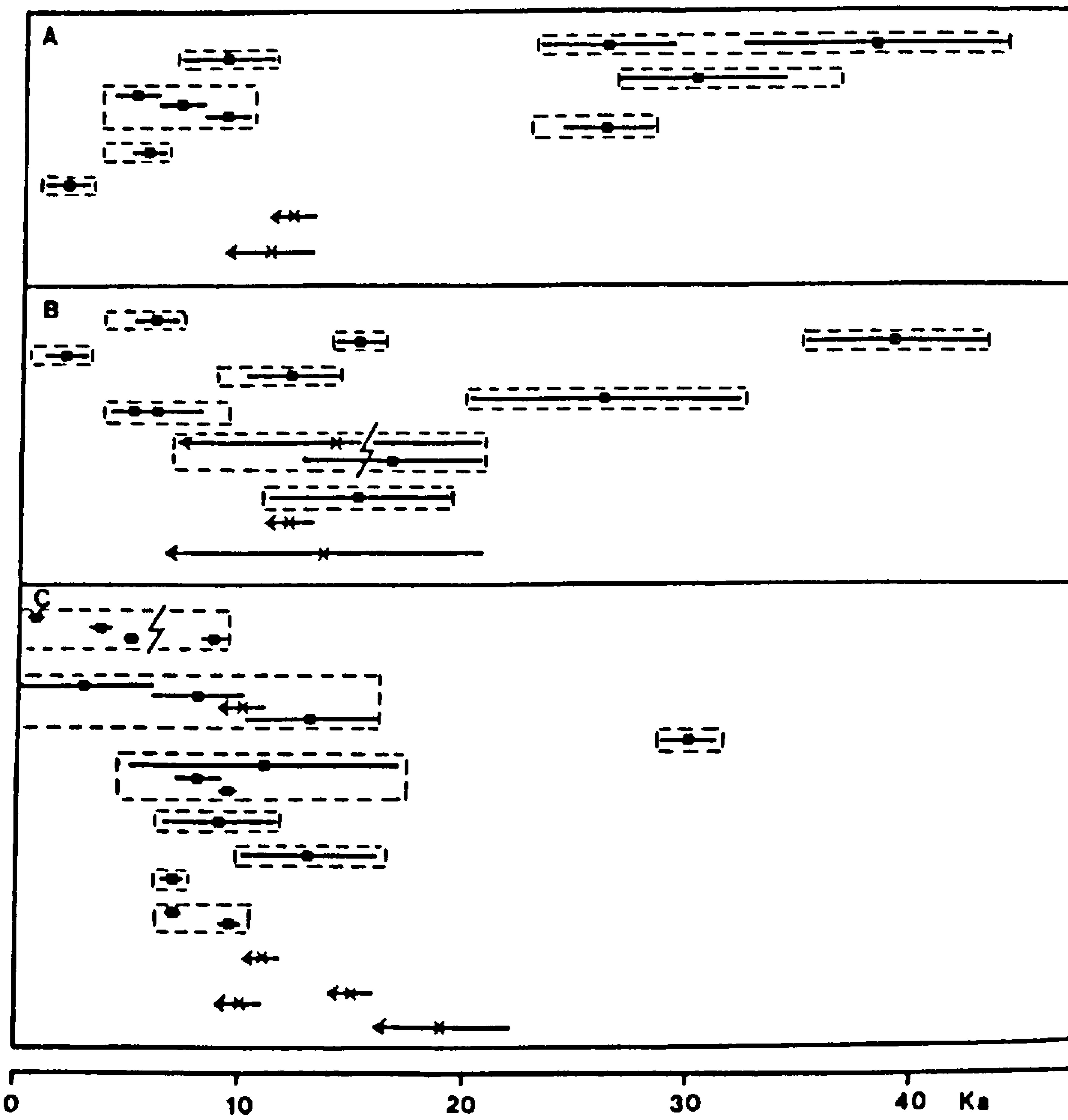
By repeated random modelling Geyh (1980) demonstrated that real gaps of one class interval can only be recognised reliably if the statistical fluctuations are smaller than ± 20%. Therefore the minimum population density required to consistently detect gaps with a width of one class interval is 25 dates per class interval. Histograms with population densities of less than 4 dates per class interval should be considered as totally unreliable. The statistical reliability of the UK speleothem age data is discussed in Chapter III.

Previous studies of speleothem growth periods in the UK have been flawed by the limited number of analyses available and the limitations of the histogram and error bar methods of graphical analysis that were used (Figure 2.1). Uranium series ages, like all radiometric dates, are always associated with a series of estimation errors resulting from analytical uncertainties, eg the half lives of ^{230}Th and ^{234}U, the tracer ratio, and the precision of the branching ratio of ^{226}Ra which will have equal alpha energies to that of ^{228}Th (Gascoyne 1977).

With uranium series analyses it has proved possible to control for or combine the majority of the different analytical errors in order to derive a combined counting uncertainty, which can be expressed as a normally distributed standard deviation about a mean value (Gascoyne 1977).

As nuclear decay is a random process, the probability that any particular atom will decay can be described by the binomial distribution. Since this probability is generally small compared to the number of atoms available to decay, the poisson distribution provides a close approximation. The amount of radioactive material and the error associated with this estimation can be determined from the number of decaying atoms that are counted (m) such that $\sigma = m$. The standard deviations of all the nuclides measured to calculate a radiometric age can be combined by error summation and this combined error should approximate to a normal distribution.

FIGURE 2.1 : UK Speleothem uranium-series ages (Gascoyne et al 1983, Atkinson et al 1986).



Typically precisions of ±10% are achieved by most laboratories (Ivanovich *et al* 1984a. Since all $^{234}U/^{230}Th$ dates are not of equal precision, graphical techniques such as fixed interval histograms based on the mean value are inappropriate since they display all dates as having equal precision. Histogram presentation of radiometric ages are usually misleading as they often don't give a good representation of growth frequency. Error bar diagrams are statistically accurate, but the number of analyses that can be shown on one diagram without confusion is limited. These problems led Hennig *et al* (1983) to propose an error weighted frequency curve method of analysis for uranium series data. Unfortunately, although their method provided a more accurate depiction than frequency histograms, it introduced a weighting of the data proportional to the mean age of the speleothems. It thus biased the data towards the older dates. Hennig *et al's* (1983) treatment of the combined errors was also simplistic, assuming a continuous distribution between ± 1 σ, whereas these errors are distributed normally about the mean (Gascoyne 1977). These difficulties can be overcome by the rigorous cumulative distributed error frequency curve technique of Gordon & Smart (1984), which is based upon two assumptions: firstly that the probability of the true age differing from the calculated age approximates a normal distribution; and secondly that the combined errors adequately reflect the size of the estimation error.

The combined errors only accurately account for the errors in measuring some of the nuclides. Most chemical errors involved in the separation of the nuclides can be controlled for by the use of tracers. However certain errors such as the spike counting uncertainty are not adequately accounted for and the combined error may therefore underestimate the size of the true error (Hennig *et al* 1983). However, this unaccounted error is likely to be relatively small compared to the combined errors.

Determination of a Cumulative Distributed Error Frequency Curve

The details of the cumulative distributed error frequency technique have previously been described elsewhere (Gordon & Smart 1984; Gordon *et al* 1987):

"The normal probability function can therefore be employed to model the distribution of true ages. Unfortunately the age is related to the $^{230}Th/^{234}U$ ratio in a non-linear manner, causing the asymmetry in quoted errors observed, particularly with older dates. To apply the normal probability function it is therefore necessary to convert the quoted ages and their upper and lower limits to $^{230}Th/^{234}U$ ratios. This requires that the $^{234}U/^{238}U$ ratio is known. The probability density for each date can then be estimated for fixed time intervals, which must also be expressed in terms of $^{230}Th/^{234}U$ ratios.

This procedure is repeated for each date, and the cumulative distribution calculated. Since each date is weighted to contribute an area of one, the frequency is expressed directly as number of dates per unit time. It is important to employ a relatively short time interval because the shortest events which can be resolved in such a series are equal to twice the time interval employed (the Nyquvist frequency). In this analysis we have employed a 500 year interval...over the period 0-350000 years."

(Quoted from Gordon & Smart, 1984.)

"Only finite dates with finite uncertainties have been included in the data set, and all dates less than 1500 years (the effective lower limit of the method) are excluded. All analyses have also been screened to ensure that the calculated ages are reliable. These analyses for which the chemical yields are known to be less than 10% are excluded, although this information is not always included in published results. A more significant problem occurs for analyses in which Leaching of ^{230}Th, and probably also uranium isotopes, has occurred from insoluble detritus (quartz grains and clays) present in speleothems. This is indicated by the presence of significant ^{232}Th, which will be absent in pure calcite containing no thorium on deposition. Various procedures have been applied to correct for this effect, but at present none of these methods can be considered reliable. We have therefore excluded all analyses for which the $^{230}Th/^{232}Th$ ratio is less than 20. Whilst this significantly reduces the available data it will enhance the clarity with which periods of active growth can be defined, and is therefore desirable."

(Quoted from Gordon *et al*, 1987)

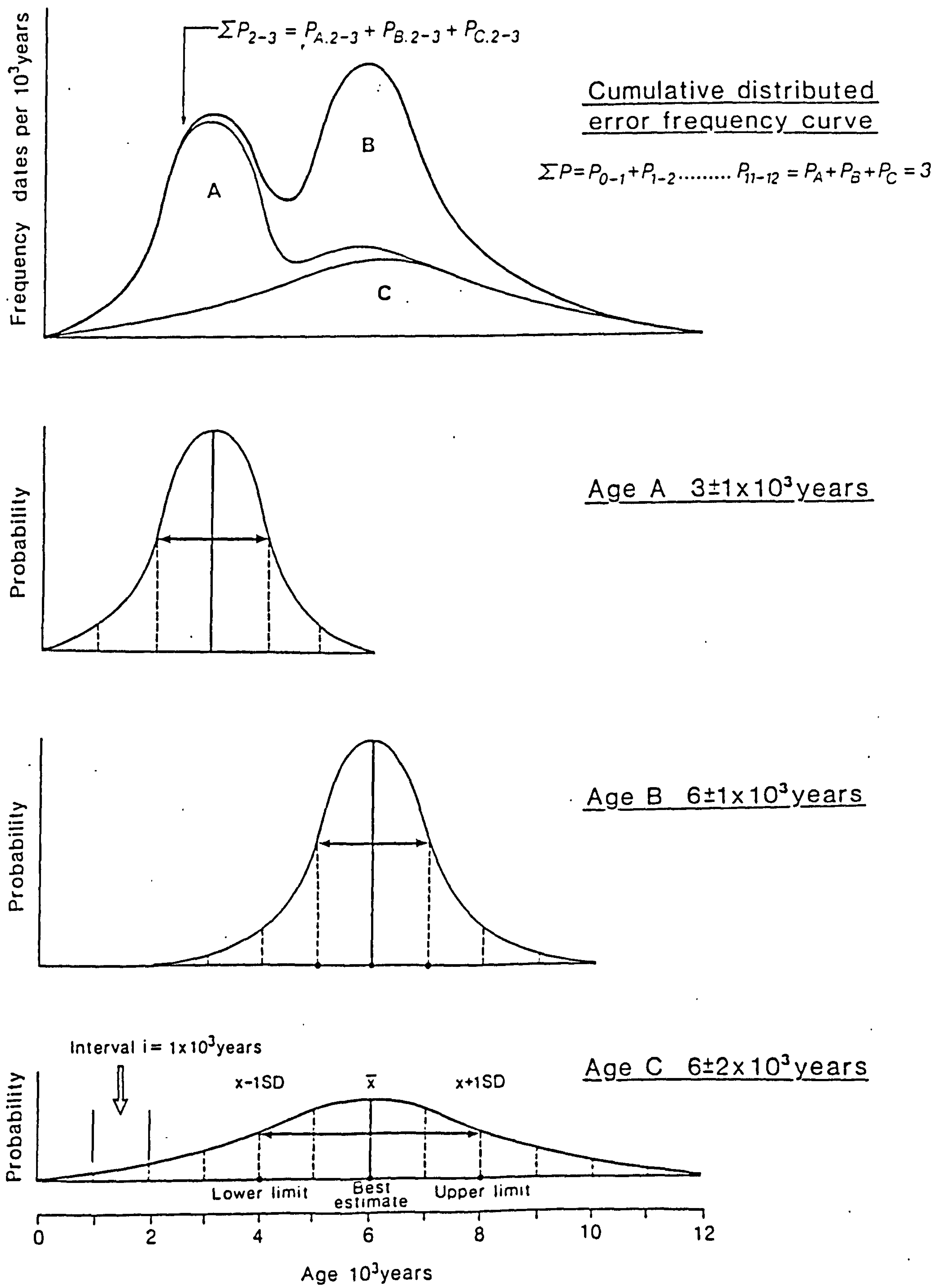
Figure 2.2 shows graphically how the method works. Analysis with relatively low counting uncertainties are represented by tall peaks with low dispersions (eg ages A and B), whereas poor analysis with high uncertainties produce flatter, broader peaks (eg Age c). The cumulative distributed error frequency curve is produced by summing the probability that each of the three ages actually lies in each of the twelve 1000 year intervals the age range is subdivided into. (Top and C in Figure 2.2)

Potential Future Developments in Speleothem Analysis

The future potential of speleothem analysis for determining the timing and magnitude of Quaternary climatic fluctuations is enormous. It is possible that the climatic signals recorded by the presence of secondary calcite deposits (particularly speleothems) in Britain are similar to those evident from the pollen record, since these two records are to some degree inter-related. The study of sub-fossil pollen allows the reconstruction of the dominant vegetation type, but rarely the exact species that composed the ecosystem. The record shows that during warm interglacial and interstadial events, favourable climatic conditions led to the invasion of thermophilous flora and eventually during interglacials to a mature forest climax community (Walker 1970). Climatic deterioration led to the reinvasion of cold tolerant flora and to progressive decline of the forests. Although the exact details of the warm periods' vegetation history vary widely, the general pattern during interglacials is consistent enough for a four stage glacial-interglacial cycle to usually be discerned. (Turner & West 1968.)

At any one site for a given range of climatic conditions each successional stage would have been characterised by a limited range of annual CO_2 production. As long as the vegetation is in quasi-equilibrium with the climatic conditions it should be theoretically possible to determine the successional stage by measuring the growth rate changes of speleothems in underlying caves. Speleothems

FIGURE 2.2 : Construction of a cumulative distributed error frequency curve (Gordon et al 1987).



invariably exhibit a complex stratigraphy resulting from variations in their deposition rates. Complete hiatuses and long periods of rapid continuous growth, resulting in large palisade crystals, are often found in single speleothems; along with many intermediate stages. The main factors directly controlling the growth of any single speleothem are the drip rate and the relative difference in PCO_2 levels between the seepage-water and the cave air (Franke 1965). By studying several speleothems in conjunction it should be possible to use dendrochronological techniques to cross-correlate their stratigraphies, thus yielding average growth rates for different growth periods. In this way it should be possible to control for variations in drip rates at any one site, as long as these variations are not so large that they completely swamp out the PCO_2 signal. However, in order to establish reliable cross-correlations, absolute dating of relatively small sections of speleothem are required to provide fixed points. Although attempts have been made to date successive growth layers of speleothems and good results obtained (Duplessey *et al* 1970), conventional uranium series analytical techniques require relatively large samples (10 to 100 grams of calcite) in order to obtain a reasonably precise analysis. Using samples of this size invariably results in homogenising sections of speleothem that exhibit different crystal structures. New dating techniques such as Mass Spectrometry and Electron Spin Resonance (ESR) may provide an accurate method of dating small calcite samples in the future (Hennig & Grün 1985; Chen *et al* 1986), but at present the construction of speleothem growth rate chronologies remains unfeasible.

C H A P T E R III

THE MENDIP AND U.K. SPELEOTHEM RECORD

As stated in the introduction the prime purpose of this thesis is to try to interpret Quaternary events in the Mendip region in the context of the wider UK and, if possible, world records. The absolute dating of speleothems by the $^{234}U/^{230}Th$ method provides an ideal opportunity for this purpose since it allows the construction of a detailed chronostratigraphic framework. If this framework is valid it will enable the direct comparison of Quaternary events in the Mendips with those elsewhere. For the purpose of unravelling the sequence of Quaternary events at an inter-regional level it is essential to obtain precise absolute dates, since both the lithostratigraphic and biostratigraphic records are incomplete, complicated by local conditions, and almost certainly time transgressive (see the relevant chapters for details). The complexity of the sequence of lithostratigraphic and biostratigraphic units in the Mendips also hinders exact inter-regional comparisons. Therefore the chronostratigraphy of the Mendips will be examined in some detail.

The Speleothem Record in the Mendips

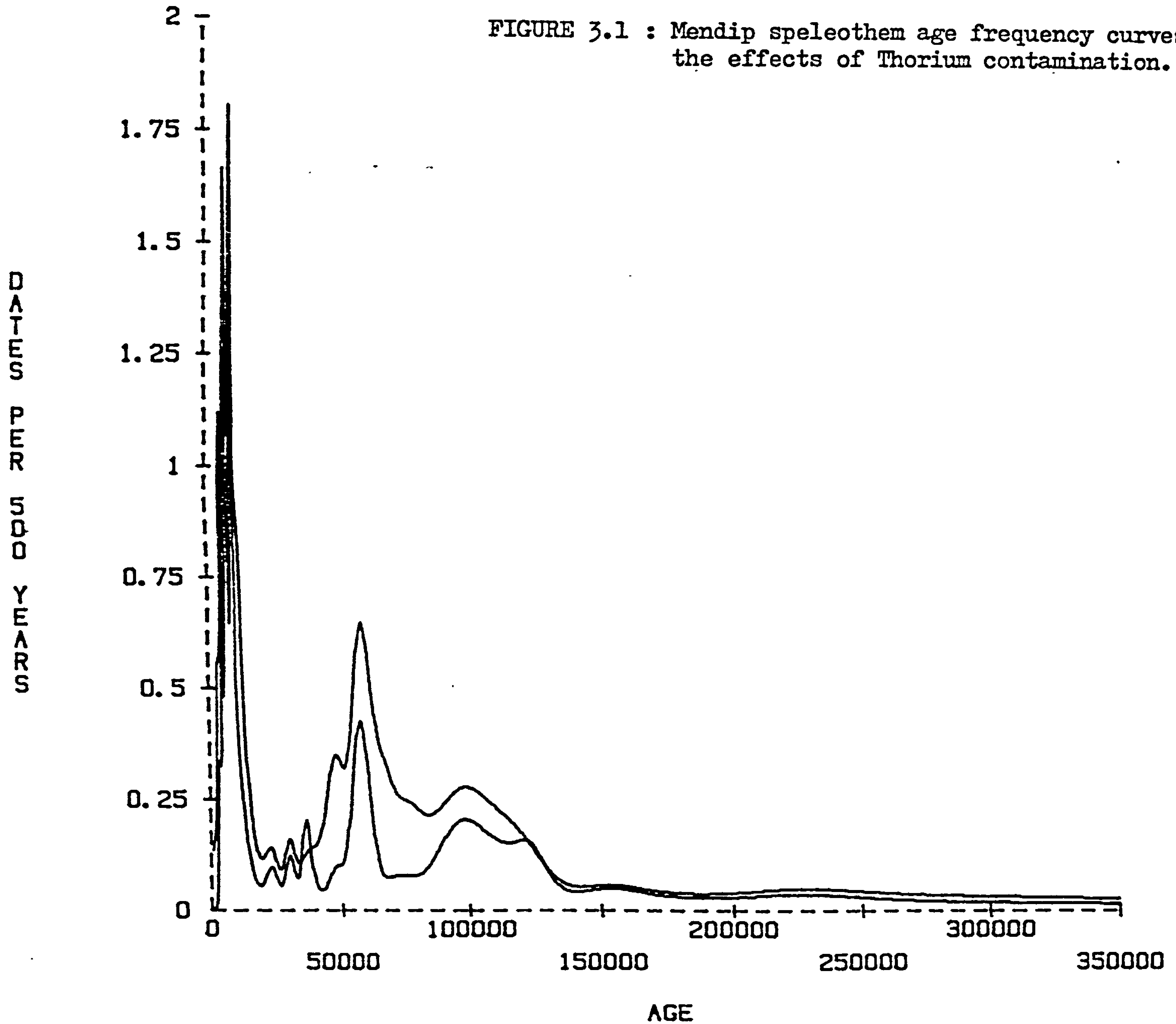
Early work on the $^{234}U/^{230}Th$ dated speleothem record from the Mendips was concentrated on GB cave, which is the swallet cave that feeds the Cheddar Gorge spring system (Atkinson *et al* 1978). Uranium series dates on 12 speleothems showed that underground drainage in GB had developed before 360000 years BP *"at which time the mouth of Cheddar Gorge lay at 90 meters above sea level, 16 meters below the plateau surface"* (Atkinson *et al* 1984.) Four speleothem growth periods were noted based on dates from GB and Yorkshire caves; they were 0 to 10000 years BP, 60000 years BP, 90000 to 145000 years BP and 170000 to 420000 years BP.

Speleothem ages from Swildon's and St Cuthbert's swallet as well as more dates from GB were published by Atkinson *et al* 1986 (In Figure 2.1). These showed that speleothems had grown continuously throughout the Holocene from c.13000 years BP to present. Atkinson *et al* (1986) also showed that the Mendip groundwater's mean Ca:Mg ratio of 11.9 and Ca:SO4 ratio of 8.3 indicated that speleothem deposition required the local presence of a soil and vegetation cover.

Although few $^{234}U/^{230}Th$ analyses of Mendip Speleothems have been published, 103 age determinations were available for analysis. Table 3.1 lists their location and the number of determinations that were considered to be reliable (see Chapter II). Most of the unpublished data was kindly supplied to me by Dr Derek Ford, Dr Pete Smart and Dr Tim Atkinson. As can be seen from the distributed error weighted frequency curves (Figure 3.1), speleothem growth in the Mendips has not been continuous over the past 350000 years,but is concentrated into a number of distinct growth periods. Extensive growth has occurred at different periods over the past 140000 years; however before that the distributed error weighted frequency curves are relatively flat. This is due to two factors: (1) the relatively small number of dates older than 140000 years BP(eg 17 out of 103) which is a consequence of the relative scarcity of preserved speleothems of this age (see Chapter II); and (2) the relatively low precision associated with these older date which have an average standard deviation of about $^{+60000}_{-44000}$ years BP.

Before discussing the climatic implications of the speleothem growth curves from the Mendips, it is necessary to consider the other factors that may affect them. Contamination of speleothem calcite by detrital thorium can lead to inaccurate age determinations even

FIGURE 3.1 : Mendip speleothem age frequency curves showing the effects of Thorium contamination.



when correction procedures are applied. Figure 3.1 demonstrates how the inclusion of contaminated speleothem age data can distort the record. The effects are particularly noticeable with the older peaks which are effectively swamped by the excess noise created by the inaccurate dates. The lower curve in Figure 3.1 is constructed from the uranium series analysis with $^{230}Th/^{232}Th$ ratios equal to or greater than 20. This value is an arbitrary one that has been widely used as indicative of an analysis in which detrital Th does not have a significant effect on the date (Gascoyne 1977; Ivanovich *et al* 1984). However, the scale of the effect of thorium contamination upon age calculations is dependent upon the total uranium and thorium content of the sample. It is probable that analyses with $^{230}Th/^{232}Th$ ratios in the low twenties and also with low uranium content should have been excluded from the calculation of the distributed error weighted frequency curves. Unfortunately the relevant data have often not been included in the published results of uranium series analysis, so no attempt at excluding these dates has been made. Further work needs to be done in this area although the number of dates affected is probably fairly small.

Inaccurate age determination can also arise from poor analysis. Inaccurate dates are often noticed from analyses where the uranium and/or thorium recovery is under 10%, as measured by the spike recovery. Theoretically this should make no difference to the age calculations as long as the total amount of uranium recovered is sufficient to obtain reliable counting statistics. However some authors have noted inconsistencies with low recovery analyses and urge caution in their interpretation (Harmon *et al*, 1977,). All analyses with recoveries less than 10% are excluded from the calculation of the distributed error weighted frequency curves (the lower curve in Figure 3.1) where these data are known. The 10% figure is again an arbitrary one and problems may arise with uranium series analysis with recoveries in the low tens. This is evident from the peak centres around 22500 years BP, which is dependent upon one date from GB cave (GB 22A) which was supplied by Dr Peter Smart.

This age was calculated for analyses with a uranium recovery of 10%. Since there is no other evidence of speleothem growth in the Mendips during the period of this date it is probably inaccurate.

The presence of low precision analysis can lead to the blurring of the record due to the noise they generate. This can be a particular problem with peaks that are situated closed together, which can merge into one large broad peak. If one of the peaks is much larger than the others it can often completely swamp the smaller peaks if many imprecise dates are present. Figure 3.2 demonstrates this problem; it shows a series of four distributed error weighted frequency curves from which dates with standard deviations larger than 100%, 25%. 15%, 10% of the mean age have been progressively excluded

The clarity with which the peaks can be resolved increases as the imprecise dates are removed. The position of the peaks also shifts as the interference from nearby peaks is reduced. This is particularly noticeable with the two peaks that lie between 80000 and 130000 years BP whose central positions move apart from 98000 to 95500 years BP and from 120500 to 123000 years BP, between the 100% precision curve and the 10% precision curve. However, as the imprecise dates are removed the total sample size from which the distributed error weighted frequency curves are calculated falls from 59 dates to 23 dates. This causes sampling error problems, particularly with the smaller peaks such as the one centred around 72000 years BP which disappears in the 10% error curve.

Sample bias will cause distortion of the Mendip's speleothem growth record. Most of the Mendip data has been obtained from speleothems in geomorphological contexts, so there is no obvious bias towards any particular period of Pleistocene interest. However, the majority of the age determination data relates to speleothems from GB cave (Table 3.1). Figure 3.3 shows the contribution that the GB speleothem age data makes to the total Mendip distributed error weighted frequency curve. The peak centred at 22500 years BP, 57000 years BP, 72000

FIGURE 3.2 : Mendip speleothem age frequency curves stripped by % error.

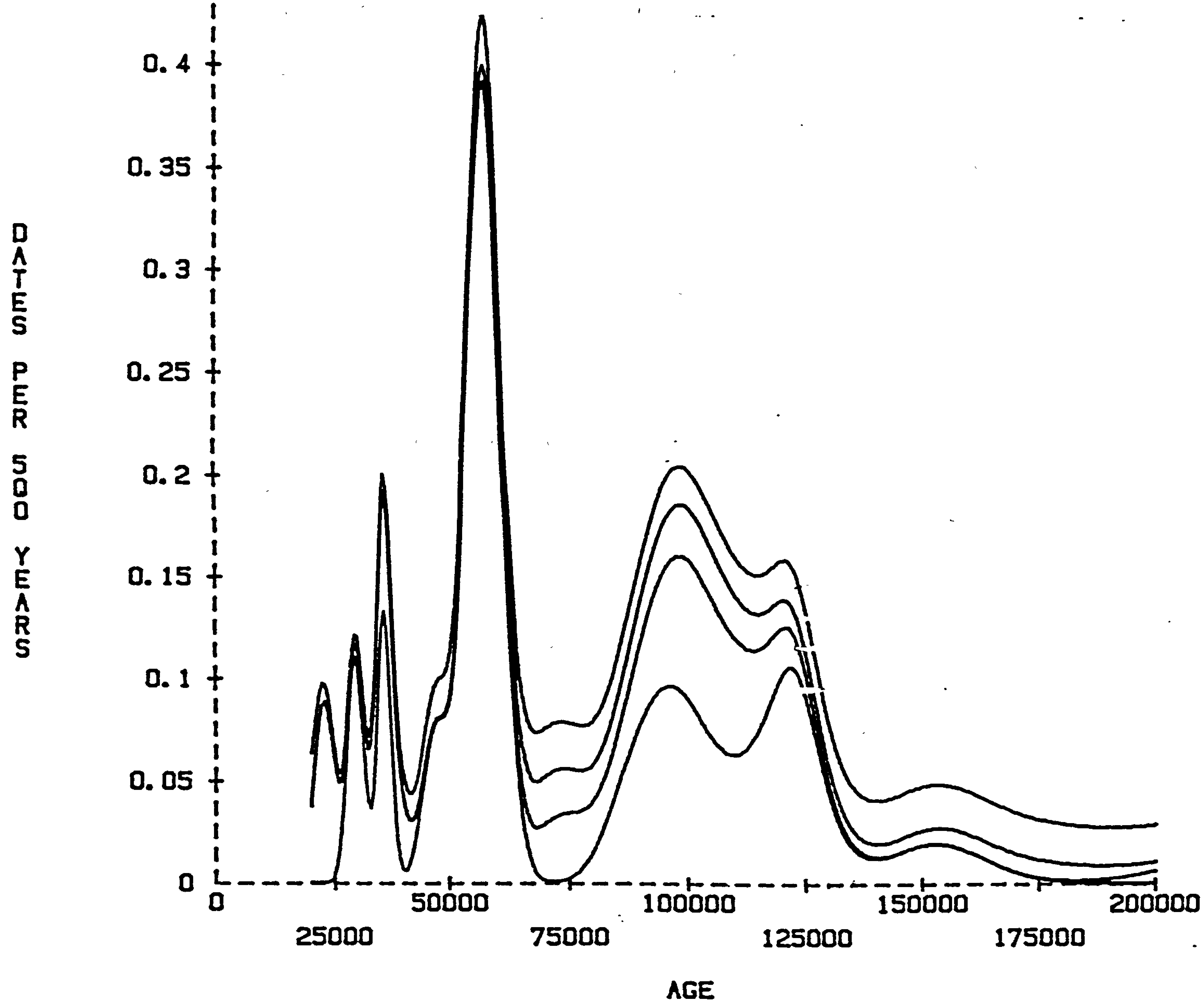
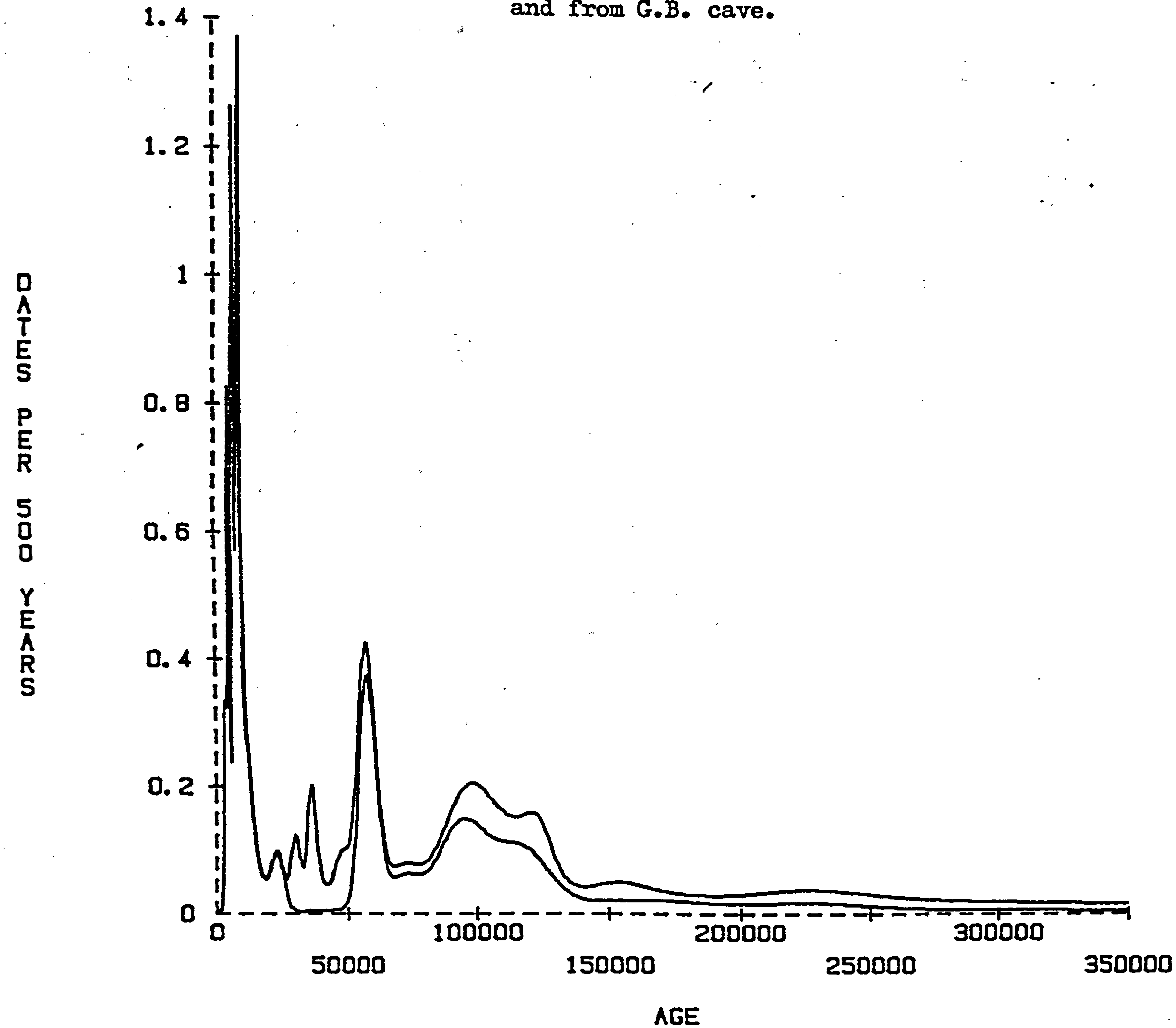


TABLE 3.1 : DISTRIBUTION & SOURCES OF THE MENDIP SPELEOTHEM DATA

Site (Grid Ref)	Analyses used	Analyses rejected	Source
GB Cave (47595623)	37	15	Atkinson et al, 1978, 1986 (29 dates) Unpublished (23 dates) DCF, TCA.
Sun Hole (46735408)	4	4	PLS - Unpublished
Picken's Hole (3969550)	4	0	PLS - Unpublished
Great Oone's Hole (46805392)	0	5	Kameli 1980
Reservoir Hole (47465447)	2	0	Kameli 1980
St Cuthbert's Swallet (54285049)	2	6	Atkinson et al 1986 (2) DCF - Unpublished (6)
Rhino Rift (48475557)	4	6	Atkinson et al 1984
Manor Farm Swallet (49825566)	0	2	DCF - Unpublished
Swildon's Hole (53125131)	1	8	Atkinson et al 1986 (2) DCF - Unpublished (7)
Bleadon Cavern (36065813)	3	0	PLS - Unpublished
	58	45	

PLS = Dr P Smart
TCA = Dr T Atkinson
DCF = Professor D Ford

FIGURE 3.3 : Speleothem age frequency curves from all Mendip caves and from G.B. cave.



years BP and 95000 years BP are strongly influenced by the GB data. The size of the 57000 year BP peak is due to repeated dating of the same flow-stone layer which was used as a standard as part of the uranium series inter-comparison project. (Harmon *et al*, 1979; Ivanovich *et al*, 1981.)

The Speleothem Growth Periods in the Mendips

By examining the complete and stripped distributed error weighted frequency curves from the Mendip speleothem data it is possible to construct a best estimate of speleothem growth periods in the Mendips (Table 3.2). 13 peaks indicative of speleothem growth are evident over the past 250000 years. However, for reasons already discussed, the three distinct peaks in the Holocene and the peak centred at 22500 years BP are considered tentative. The remaining nine peaks have been labelled Mendip 1-9 (Men 1-9) in accordance with standard stratigraphic practice that regional stratigraphies should be constructed consecutively using local stage names. (Hedbury 1976.)

The major problem with identifying the precise periods of speleothem growth in the Mendips is the limited number of dates available. The nine resolved peaks may not accurately represent the total number of speleothem growth periods over the past 250000 years BP. A number of periods may not have been resolved because the small sample size has led to sampling error. Table 3.2 shows the estimated number of dates which contribute to each peak $\pm 2\sigma$ and the sites from which these speleothems came. The frequency of dates per peak has been estimated graphically rather than by statistical modelling or spectrum stripping and the numbers have been rounded to the nearest 0.5 of a date. Only the peaks centred at 57000 years BP (Men 4), 90500 years BP (Men 6), and 123000 years BP (Men 7) have probability densities greater than 4 at the $\pm 2\sigma$ level. If the conclusions of

TABLE 3.2 : PLEISTOCENE SPELEOTHEM GROWTH PERIODS FROM THE MENDIP REGION

Peak designation.	Best estimate of peak centre pos.	Estimate of the no. of dates represented by peak at 2σ	Site with speleothem dates contributing to the peak.
MEN 1	29500	1	St Cuthbert's Swallet
MEN 2	36000	2	St Cuthbert's Swallet Sun Hole
MEN 3	47000	4	Rhino Rift
MEN 4	57500	14.5	GB Cave Rhino Rift Picken's Hole
MEN 5	72000	2.5	GB Cave Picken's Hole
MEN 6	95000	10.5	GB Cave Sun Hole Swildon's Hole Bleadon Cavern Picken's Hole
MEN 7	123000	7.5	GB Cave Sun Hole Bleadon Cavern
MEN 8	153000	3	GB Cave Picken's Hole Bleadon Cave Reservoir Hole
MEN 9	227000	2.5	GB Cave Sun Hole Bleadon Cavern Reservoir Hole Picken's Hole

Geyh (1980) are correct then the statistical significance of all the other peaks should be considered unreliable.

In order to establish the reliability of the Mendip speleothem growth record one must therefore compare it with the much larger UK record. If nine periods of speleothem growth are present over the past 250000 years, this would indicate that there have been considerably more interglacial and interstadial stages during this period than are currently recognized from the lithostratigraphy and biostratigraphy of the Mendip region. It is obviously of prime importance to determine accurately when interstadial and interglacial conditions occurred in the Mendips, in order to assess the timing and completeness of the conventional stratigraphic record. This is evident even though the middle and upper Pleistocene has been characterized by much longer periods of cold climatic conditions than warm climatic conditions (Shackleton & Opdyke 1973, 1976). Our knowledge of warm climate sedimentation is much greater than that of cold climatic sedimentation and the information retrievable from interglacial and interstadial deposits is correspondingly greater.

UK Speleothem Growth Records

520 uranium series analyses are available from the UK:517 on speleothem calcite and three from the tufa from the lower channel at Marsworth. 329 of these analyses have been taken from published sources while the remaining 192 have been supplied by Dr Pete Smart, Dr Tim Atkinson, Dr Pete Rowe and Dr Noel Christopher. (See Appendix VII.)

The geographical distribution of the areas of dated deposits is shown in Figure 3.4 and the number of analyses and sites from which these analyses came is shown in Table 3.3. Once unreliable analyses have been removed a total of 341 are available for the construction of a distributed error weighted frequency curve for the United Kingdom. Approximately 40% of these dates come from Northwest Yorkshire

FIGURE 3.4 : Speleothem sample areas in the UK
(Gordon et al 1987)

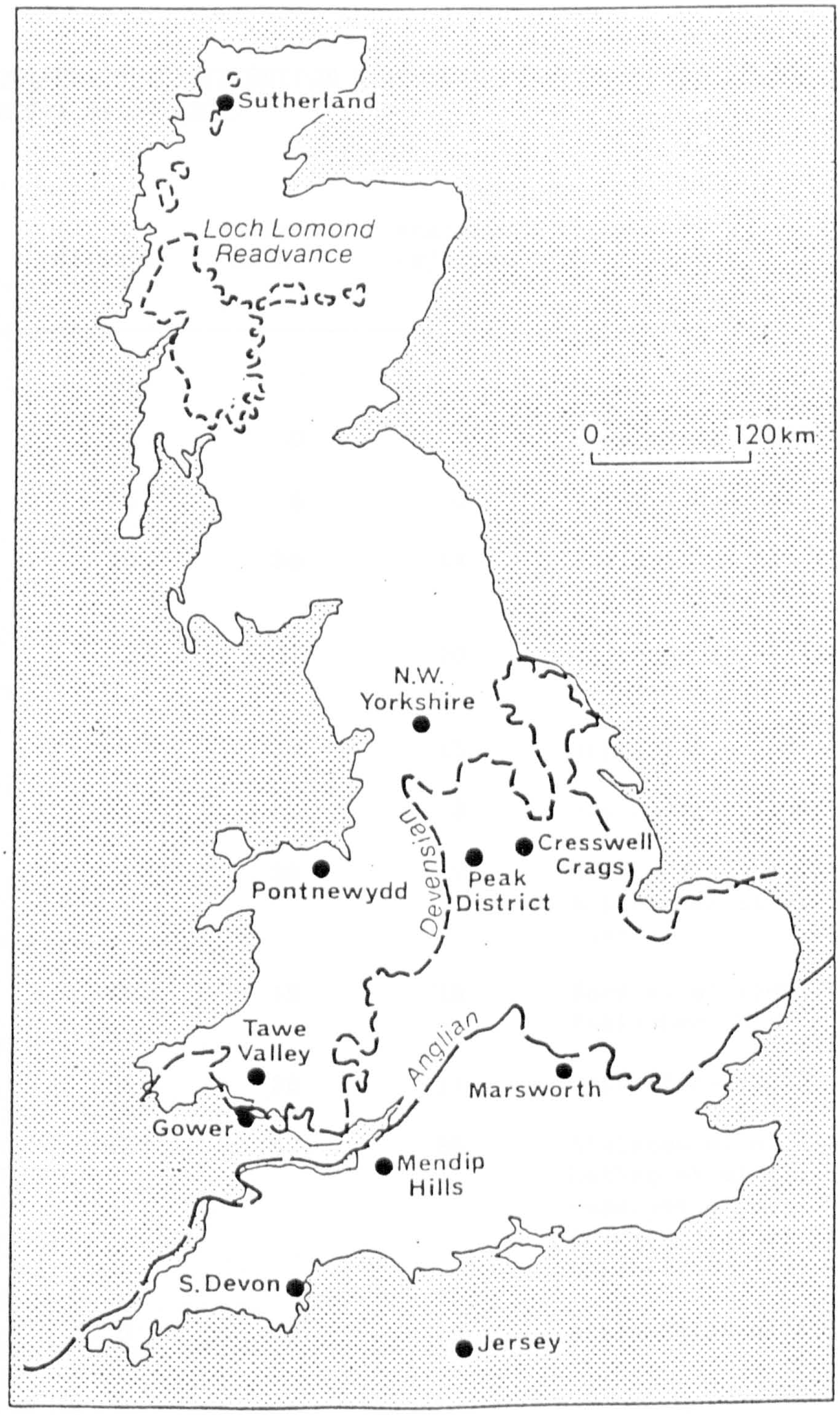


TABLE 3.3 : GEOGRAPHICAL DISTRIBUTION & SOURCES OF URANIUM SERIES ANALYSIS (Gordon *et al* 1987)

Area	No. Sites	Analyses used	Analyses rejected	Source
Jersey	1	0	1	Keen et al (1981)
S. Devon	1	4	0	Unpublished (4)
Mendip Hills	10	59	44	Atkinson et al (1978, 1984); Unpublished (89)
Gower	2	11	20	Stringer et al (1986); Sutcliffe & Currant (1984)
Tawe Valley		16	13	Unpublished (29)
Marsworth	1	1	2	Green et al (1984)
Pontnewydd	1	39	7	Schwarcz, Ivanovich et al & Debenham et al in Green (1984)
Peak District	15	19	16	Ford et al (1983); Published (6)
Creswell Crags	4	26	11	Unpublished (37)
N.W. Yorkshire	12	157	63	Atkinson et al (1978); Latham et al (1979); Gascoyne et al (1983;) Sutcliffe et al (1985;) Unpublished (2)
Sutherland	5	9	2	Atkinson et al (1986)
TOTAL	57	341	179	

because of the extensive work of Gascoyne *et al* (1983). The remaining analyses are spread evenly between south and central Britain, with about 35% of the sample lying south of the southern limits of the Devensian ice sheets. Uranium series analyses from Pontnewydd, Gower, Marsworth, South Devon, Jersey and, to some extent, the Creswell Crags region are generally associated with fossiliferous Quaternary deposits; in the remaining regions dating has generally been carried out exclusively for geomorphological purposes. The data from Marsworth, Pontnewydd, Jersey and South Devon are all restricted to one site each and may therefore only relate to local conditions at those sites, whereas the data from the remaining regions are widely spread between sites and are therefore probably indicative of general regional conditions. There is no compelling evidence that any of the secondary calcite deposits analysed have been formed by any mechanism other than CO^2 outgassing resulting from elevated partial pressures of soil air CO^2 indicative of a vegetated environment. The only exceptions are possibly some of the Devensian speleothems from Bacon Hole Cave, Gower, which may have grown by evaporation, although the evidence for this is inconclusive. (Stringer 1977,Stringer *et al*, 1986)

The cumulative distributed error weighted frequency curve for the UK data is shown in Figure 3.5 and is generally similar to that of the Mendip's. The UK curve also shows similar problems of peak interference and merging to the Mendip curve. It is possible to use the same error stripping procedure to achieve better resolution of the peaks as was used with the Mendip data (Figure 3.6). From comparison of the complete and stripped records it is possible to derive a composite best high resolution estimate of the age and number of speleothem growth periods over the past 200000 years BP (Figure 3.7). Before this date the curve is too flat to obtain any reliable information. Ten peaks relating to speleothem growth periods are resolved and these have been labelled Devensian 1-6 (Dev 1-6), Ipswichian 1-3 (Ip 1-3), and Pre-Ipswichian 1 (Pre-Ip 1) in accordance with the stratigraphy of Mitchell *et al*, 1973. The

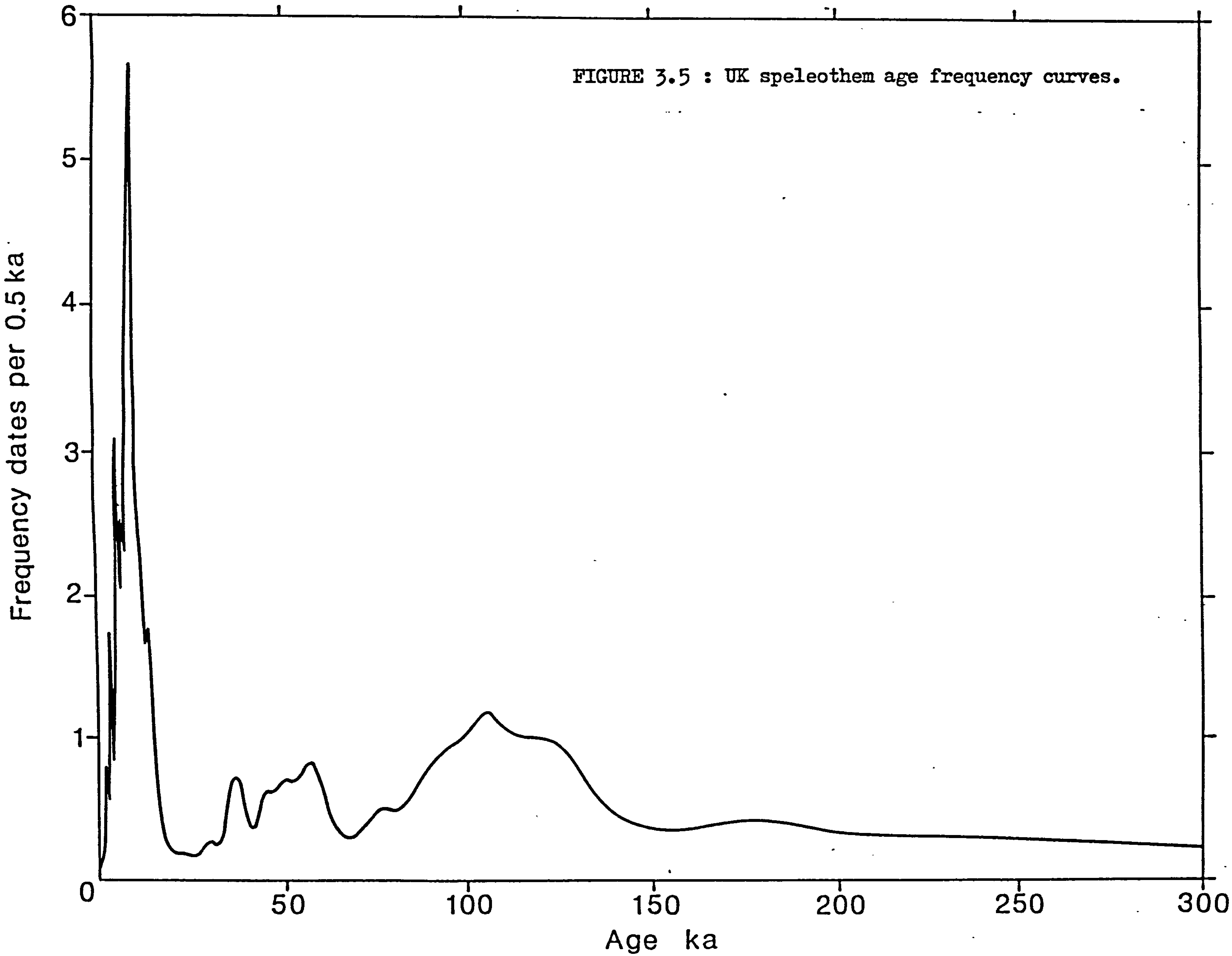
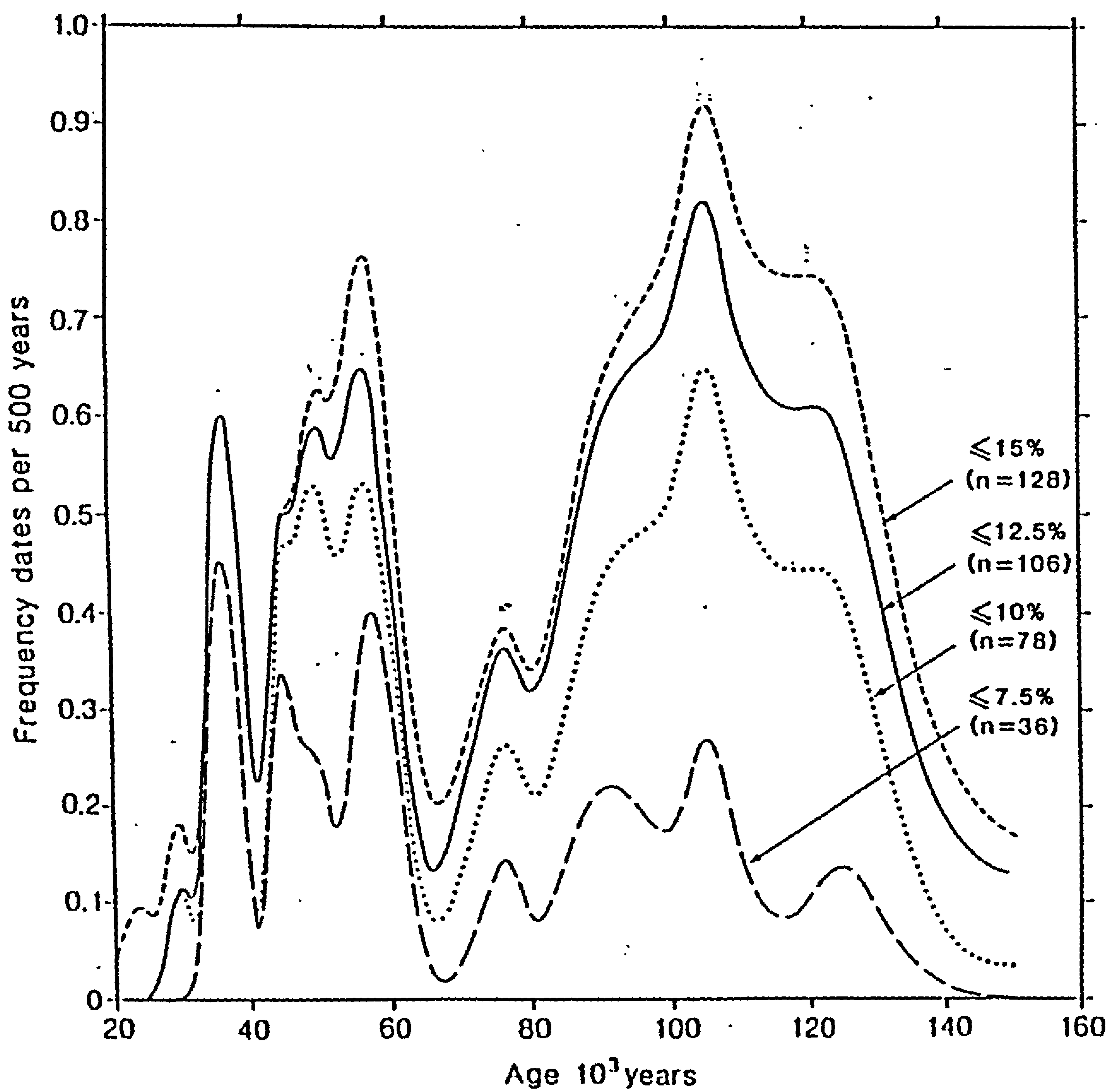


FIGURE 3.5 : UK speleothem age frequency curves.

FIGURE 3.6 : UK speleothem age frequency curves stripped by % error,



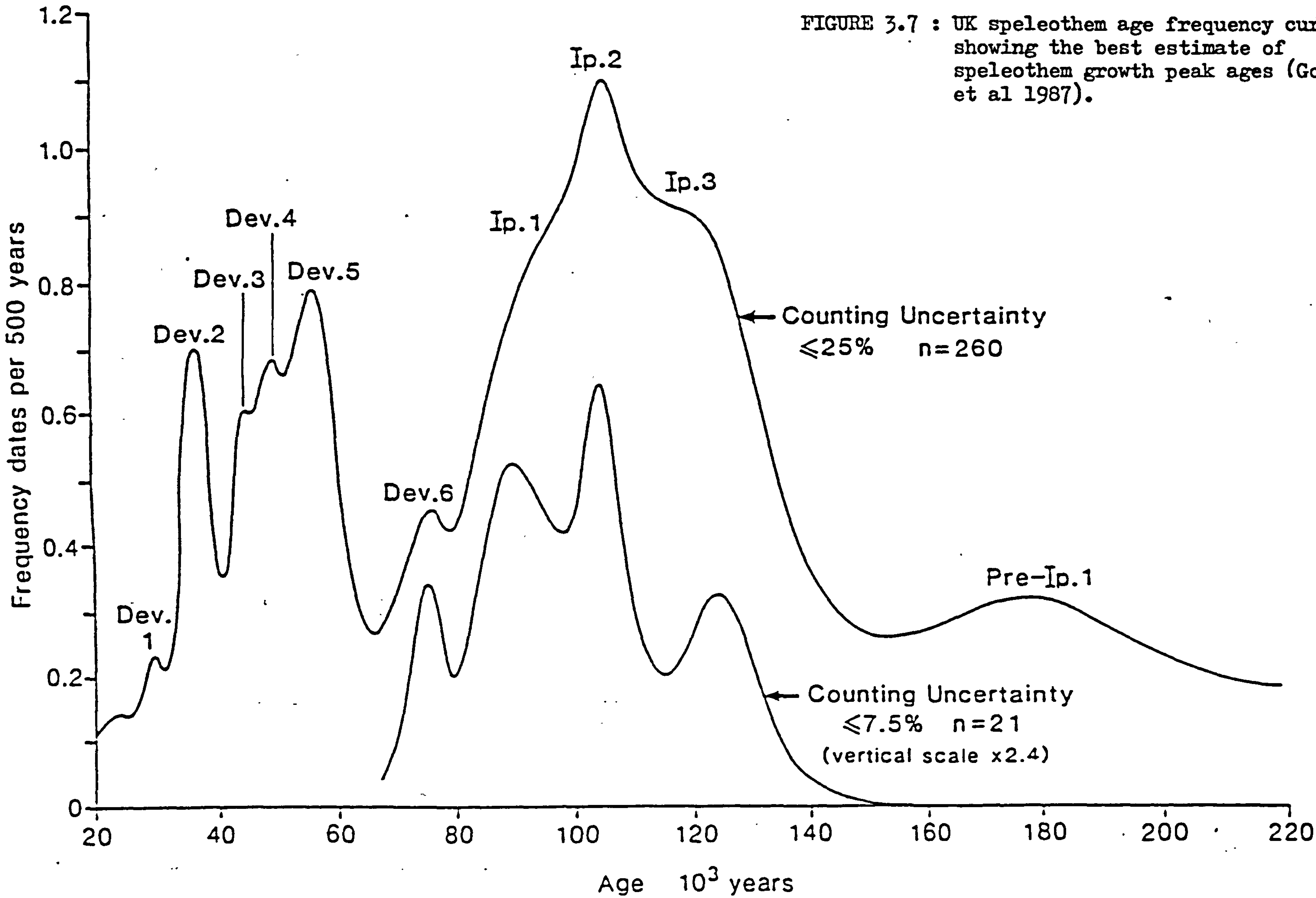


FIGURE 3.7 : UK speleothem age frequency curves showing the best estimate of speleothem growth peak ages (Gordon et al 1987).

position of the Devensian-Ipswichian (glacial-interglacial) boundary has been taken to be 80000 years BP for reasons that will be discussed in Chapter IV. This date corresponds with a marked decline in the amount of speleothem growth in the UK, which is indicative of reduced vegetation growth and climatic deterioration. The peak at 180000 years BP has been labelled Pre-Ipswichian because of the considerable doubt which has been expressed about the stratigraphic status of the Wolstonian stadial (Bristow and Cox 1973; Cox 1981; Perrin *et al* 1979; Sumbler 1983). Comparison of the number and ages of the UK speleothem growth peaks obtained from the best composite high resolution estimate of speleothem growth frequencies (Figure 3.7) with that of the best estimate Mendip data is shown in Table 3.4. Considering the small size of the data sample from the Mendips, the degree of agreement is remarkable. The ages of peaks Men 1 and Men 2 and Dev 1 and 2 are the same. The correspondence between Men 3 and Dev 3 and Men 4 and Dev 5 is also extremely close; however no peak corresponding to Dev 4 is resolved in the Mendip record. This is probably because of the size of the Men 4 peak which would swamp a smaller peak of Dev 4 age. The 47000 year BP date of the Men 3 peak is also probably older than the true age because of interference from the large Men 4 peak. Correspondence between the Men 5 peak and the Dev 6 peak is also close considering the small number of dates represented by this peak. Although there is close correspondence during the Devensian between the Mendip and UK data the peaks of Ipswichian age do not match as well, with no peak of Ip2 (10500 years BP) age being resolved from the Mendip record. This may be due either to sampling error, which seems unlikely, or to interference from the Men 6 and Men 7 peaks.

There are seven age determinations that lie between 100000 and 110000 years BP from Mendip caves. These dates are from GB cave (2), Sun Hole, Swildon's Hole (3) and Bleadon cave. However the three dates from Swildon's Hole have $^{230}Th/^{232}Th$ ratios less than 20. It seems

TABLE 3.4 :ESTIMATED AGE OF SPELEOTHEM GROWTH PERIODS FROM THE UK AND THE MENDIPS

(All dates in years BP))

UK peak designation.	Best estimate of peak centre position.	Mendip peak designation.	Best estimate of peak centre position.
DEV 1	29500	MEN 1	29500
DEV 2	36000	MEN 2	36000
DEV 3	45000	MEN 3	47000
DEV 4	50000		
DEV 5	57000	MEN 4	57500
DEV 6	76000	MEN 5	72000
IP 1	90500	MEN 6	95500
IP 2	105000		
IP 3	124000	MEN 7	123000
		MEN 8	153000
PRE-IP 1	180000		
		MEN 9	227000

probable that speleothem growth did occur in the Mendips around the 105000 years BP, but that this peak is not resolvable by the error stripping method due to the sparse number of dates currently available from the Mendips.

There is strong evidence for speleothem growth at 105000 years BP from northwest Yorkshire. Gascoyne et al (1983) reported *"With one exception (77162), all the speleothems that grew in the period 130-90 ka contain a growth hiatus marked by a thin layer of clastic sediment or an erosion surface. While the precision of dating does not allow us to define the episode very precisely, the renewal of growth is dated at about 105 ka. This district-wide, synchronised hiatus is presumably due to a brief climatic shift, such as a cool phase, a period of intense flooding, or a period of regional aridity.......A cooling in the interval 110-105 ka is independently confirmed by stable isotopic studies of two of these deposits."*

The divergence of the ages of the Men 6 (95500 years BP) and Ip1 (90500 years BP) peaks and the Men 7 (123000 years BP) and Ip 3 (124000 years BP) peaks is also a result of peak interference. The central positions of the Men 6 and 7 peaks being pulled towards one another, away from the true ages. However, the discrepancy of 5000 years between the Men 6 and Ip 1 peaks is much larger than the 1000 years discrepancy between the Men 7 and Ip 3 peaks. This difference may be partly explained by the possible inclusion of a peak corresponding to Ip 2 (105000 years BP) within the Men 6 peak, but it may also be partly due to the possibly time-transgressive nature of some of the peaks. It is possible that due to the southerly position of the Mendips, vegetation may have colonized this region during some interstadial and interglacial periods earlier than the average date of colonization of the UK as a whole, which is recorded in the UK distributed error weighted frequency curve.

The non-correlation of the Men 8 (153000 years BP) and Men 9 (227000 years BP) peaks with the pre-Ipswichian 1 peak (180000 years BP) is of little significance considering the sparsity of data in this region of the curves. It is impossible to say which of these peaks is reliable. It may be that the Mendip peaks reflect the true record and the pre-Ipswichian 1 peak just represents an amalgamation of these two separate peaks. Alternatively the position of the pre-Ipswichian 1 peak may be correct and the Men 8 and 9 peaks may be purely statistical artefacts. In future more precise dating of older speleothems may resolve this problem. (See Appendix 1.)

Reliability of the UK Record

Even though there is excellent agreement between the Mendip and total UK speleothem growth records, the fact that ten peaks can be identified between 20000 and 200000 BP requires further analysis of the reliability of the UK record. Since these speleothem growth records are indicative of interstadial and interglacial events and currently only one interglacial (the Ipswichian) and four Devensian interstadial events (Wretton, Chelford, Brimpton and Upton Warren) are recognized in the "pollen-based" UK Quaternary stratigraphy (Mitchell *et al*, 1973; Bryant *et al*, 1983a) as lying between 20000 and 200000 years BP. The speleothem record indicates that the "pollen-based" UK stratigraphy is incomplete and in need of revision. In order to substantiate this claim all the peaks must be shown to be statistically reliable. The ten peaks recognized are all associated with more than four dates but less than twenty-five at the $\pm 2\sigma$ level. They all therefore fall within the range of statistical reliability but not extreme statistical reliability as defined by Geyh (1980).

The stability and reliability of the UK distributed error weighted frequency curve has been tested to determine the extent to which it may be biassed by the inclusion or exclusion of particular analyses. Five curves were constructed after the random abstraction of 100 analyses (approximately 30% of the data) from the reliable data set (341 dates). The results are shown in Figure 3.8 for the interval between 20000 and 140000 years BP (only four of the five curves are

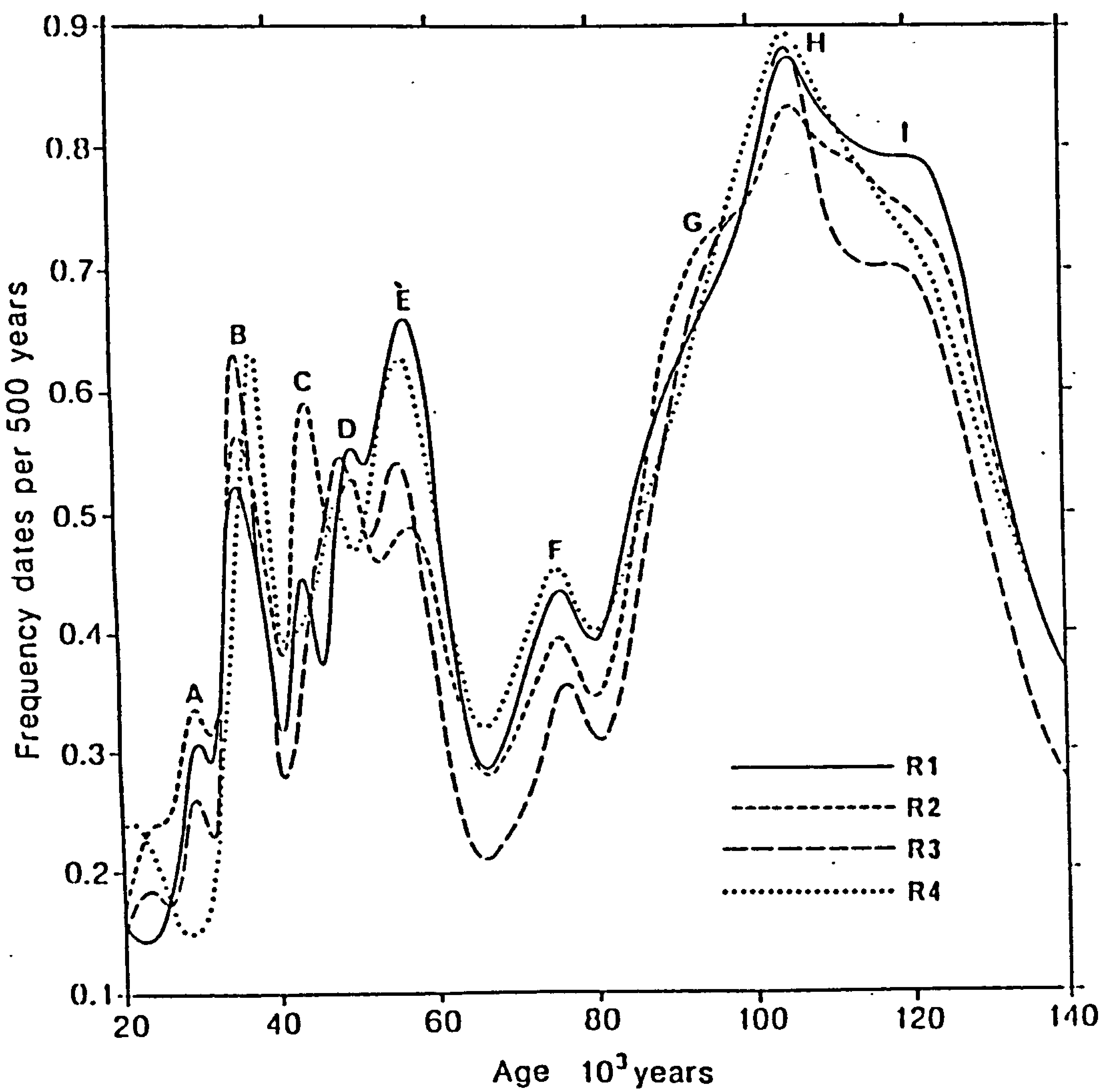


FIGURE 3.8 : UK speleothem age frequency curves from which 30% of the data has been removed by random sampling. (Gordon et al 1987)

shown to avoid confusion). As would be expected the stability of the peaks is dependent upon their size, with the main peaks being more stable than the minor peaks, which occasionally disappear because of sampling error (peak A in R4 and C in R3). Although the magnitude of the peaks is relatively variable the temporal stability is remarkably high (Table 3.5). The temporal stability seems unaffected by the peak heights and only ranges by a maximum of 2500 years. In the case of peak B this stability is indicative of the reliability of the data set as a whole.

Speleothem Growth Periods and Milankovitch Cycles

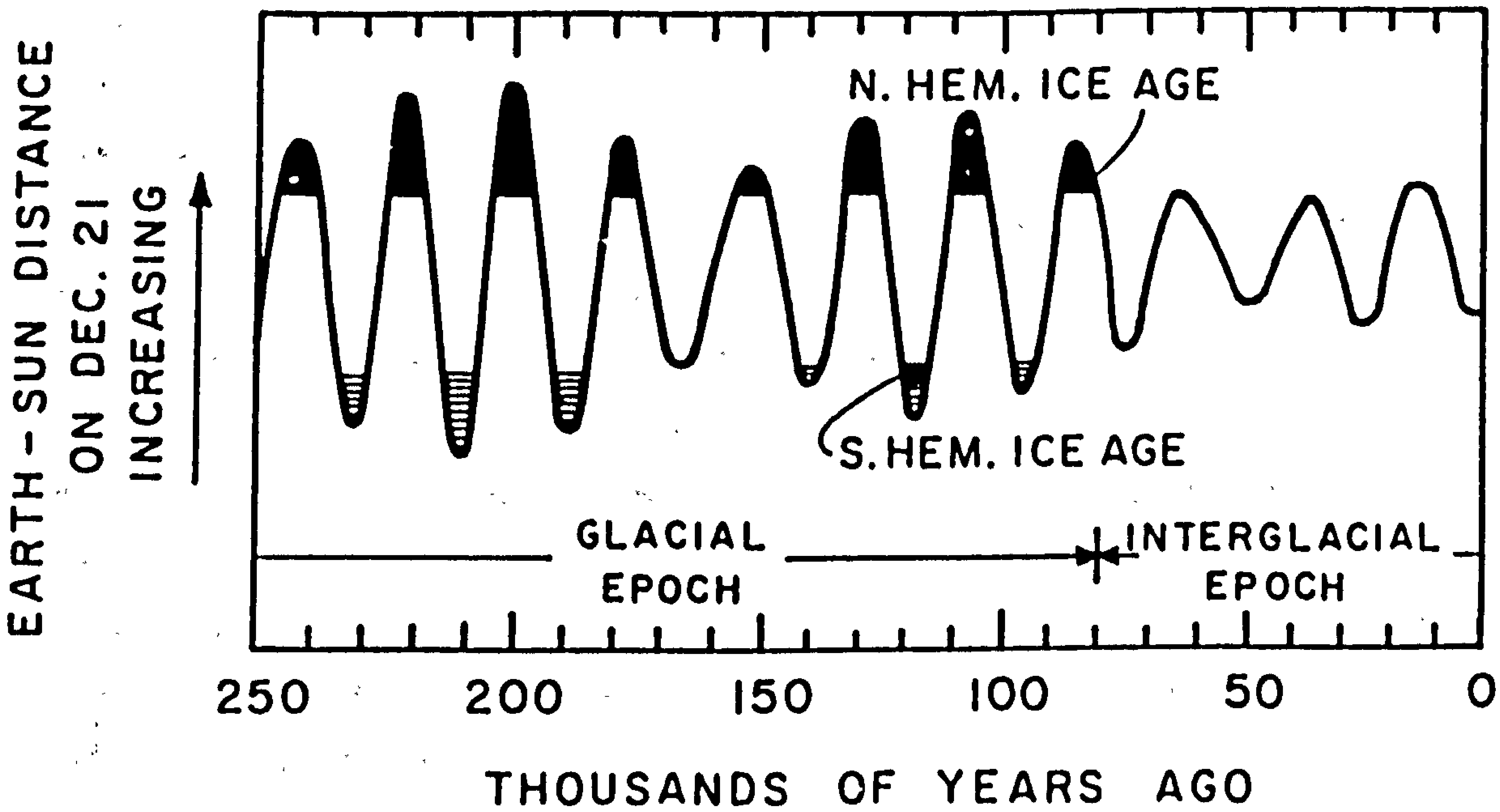
It is widely accepted that the large scale climatic fluctuations which occurred during the Pleistocene are largely controlled by astronomical forcing (Broecker *et al*, 1968; Broecker & Van Donk, 1970; Hays *et al*, 1976; Berger, 1977; Imbrie & Imbrie, 1979). During the 1920s and 1930s Milankovitch extended the work of Adhémar (1842) and Croll (1875) and proposed that the combined effects of three orbital parameters (obliquity, tilt and precession) had a climatically significant effect on the amount of solar insolation reaching the earth's surface. Although the combined effect of these orbital parameters only caused a few percentage variation in the amount of solar insolation, this was considered enough to be the prime driving mechanism for Pleistocene climatic change (Figure 3.9). The periodicities of the obliquity, tilt and precession cycles are accurately known (they are respectively about 100000 years, 41000 years and 22000 years) and their effects can be combined to produce precisely dated solar insolation curves (Milankovitch curves) for any given latitude (Kukla, 1969; Berger, 1978). There is a considerable body of evidence that suggests that although Milankovitch forcing controls the periodicity of Quaternary climatic fluctuations, other factors trigger the exact timing of interglacial, interstadial and glacial events (for example: Bray 1977, 1979; Nilsson 1983).

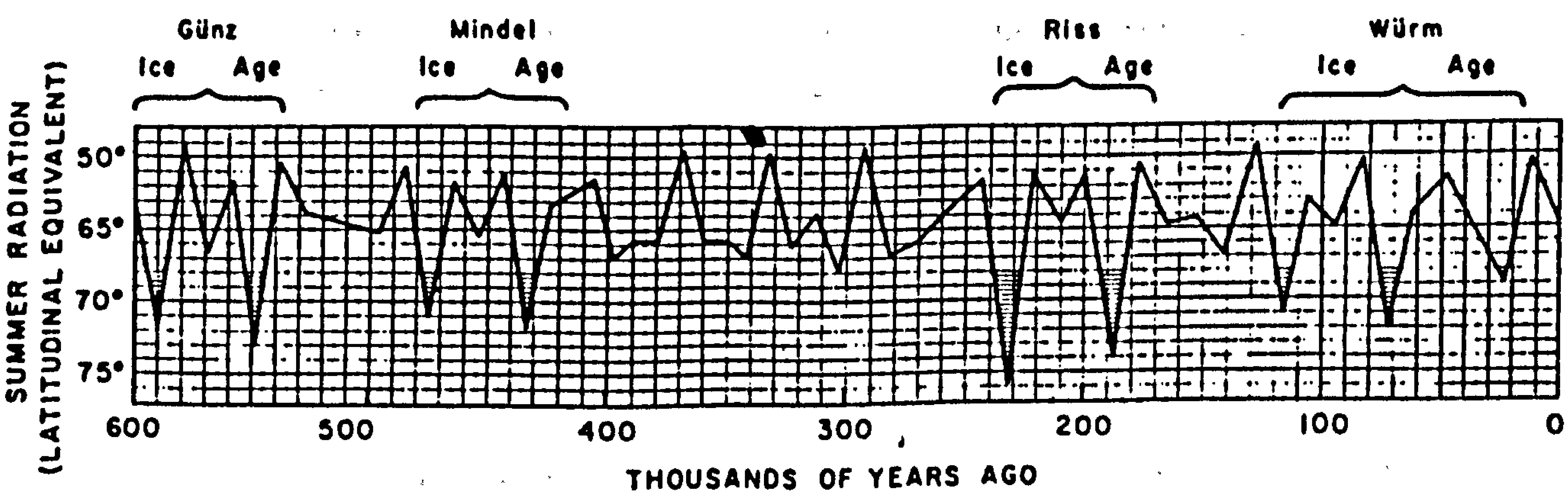
TABLE 3.5 : VARIATION OF PEAK AGE AND PEAK HEIGHT FOR 5 RUNS FROM WHICH 100 ANALYSES HAVE BEEN ABSTRACTED AT RANDOM FROM THE MAIN DATA SET. PEAKS ARE LETTERED ON FIGURE 3.9.

Peak	Peak Age x10 yr BP		Peak Height Dates per 500 years	
	-/x	Range	-/x	SD
A**	29.5	0.5	25.7	1.9
B	36.5	2.5	56.9	6.5
C*	44.5	0.5	42.4	8.9
D	49.5	2.0	49.3	4.0
E	57.0	1.5	54.3	7.6
F	76.0	1.0	37.9	3.3
H	105.5	1.5	85.9	3.2
I	119.5	1.5	72.8	3.2

* = Peak absent in 1 run
** = Peak absent in 2 run

FIGURE 3.9 : Croll's theory of the ice ages and Milankovitch's original radiation curves for latitude 65° North (after Imbrie & Imbrie 1979).





If speleothem growth in the UK is dependent upon interstadial and interglacial conditions then it would be expected to broadly correlate with the Milankovitch cycles. This comparison should provide a rigorous test for the hypotheses that the distributed error weighted frequency curve method using $^{234}U/^{230}Th$ ages provides a way of identifying and absolutely dating speleothem growth periods. Mörner (1972) has used the Milankovitch curves of Kukla (1969) to predict the periods during which the major warm and cold stages occurred over the past 130000 years. Table 3.6 shows the correspondence of these periods with the centre position of the UK speleothem growth peaks (Figure 3.7 and Table 3.4).

The degree of correspondence is remarkable, with nine out of the ten speleothem growth peaks falling within the periods of warm climate predicted by Mörner (1972). The degree of lag between the astronomical forcing and speleothem growth varies from period to period, as would be expected if it is dependent upon the re-invasion of vegetation into the UK. The only anomalous peak is Dev 2 (36000 years BP) which falls during a predicted stadial period. Despite the fact that the age of Dev 2 varied by the greatest amount in the random sampling experiments, the presence of speleothem growth in the UK at around 36000 years BP is conclusive. Speleothems of this age are found from practically every Karst region in Britain, and examination of speleothem stratigraphy also supports growth during Dev 2. Speleothem 79121 from Lancaster Hole, Northwest Yorkshire contains a hiatus between the base of the speleothem which has been dated to 44000±1000 years BP and the top which has been dated at 35000±1000 years BP (Gascoyne *et al*, 1983c). This supports the idea of two speleothem growth peaks of Dev 3 (45000) and Dev 2 age (36000) separated by a period of non-deposition.

The internal consistency of the speleothem growth record and the correspondence of speleothem growth peaks with interstadial and interglacial conditions, as predicted by the Milankovitch cycle, indicates that the conventional "pollen-based" UK Quaternary

TABLE 3.6 : COMPARISON OF UK SPELEOTHEM RECORD AND GLOBAL WARMING PERIODS CALCULATED FROM MILANKOVITCH FORCING FUNCTIONS

UK SPELEOTHEM RECORD		GLOBAL WARMING PERIODS (after Mörner 1972)	
Peak Designation	Best estimate of Peak Centre Age	Age	Nature of Period
DEV 1	29500	23000 ↓ 32000	Interstadial Complex
DEV 2	36000	?	
DEV 3	45000	40000 ↓ 45000	Interstadial
DEV 4	50000	47000 ↓ ↓ ↓ 60000	Interstadial
DEV 5	57000		
DEV 6	76000	72000 ↓ 83000	Interstadial
IP-1	90000	83000 ↓ 94000	Stadial/Interstadial/Stadial
IP-2	105000	94000 ↓ 105000	Interglacial
IP-3	124000	116000 ↓ 128000	Interglacial
PRE-IP 1	180000		

stratigraphy is in need of revision. Over the past 130000 years 1 interglacial and 4 or possibly 5 Devensian interstadials are recognised. The Ipswichian interglacial has been correlated on palynological evidence with the Eemian interglacial of the Continent (Phillips 1974), and has therefore been assumed to have a duration of approximately 11000 years based on varve counts from Eemian sediments (Turner 1975); and a thermal maximum circa. 120000 years BP based on correlation of the Eemian with stage 5e the oxygen-isotope deep sea record (Mangerud *et al*, 1979; Turon 1984). However, considerable doubt has been expressed over the integrity of the Ipswichian interglacial, particularly since no one site has yet been found which spans the entire interglacial. Therefore the interglacial is composite in nature (Hall, 1980). All the sites currently assigned to this single interglacial period may represent 2 or possibly 3 such periods. The "Ipswichian" faunal evidence supports such a division (Sutcliffe 1975, 1976 ; Sutcliffe & Kowalsky 1976; Stringer & Currant 1981) and this would be consistent with the evidence of pollen records from long cores on the Continent. Three interglacial events are recorded from Grand Pile, France (Woillard 1978) and from Tenagi Phillipon in Greece (Wijmstra and Van der Hammen 1974). A re-examination of the long pollen cores from southern Spain (Florschutz *et al*, 1971) has also indicated the presence of 3 interglacial periods (Wijmstra *pers.comm.*). It is tempting to correlate these 3 interglacials with the Ip 1-3 peaks of the UK speleothem growth record and/or the 3 oxygen isotope peaks of stage 5 of the deep sea record (see Chapter IV).

The Wretton interstadial is conventionally thought to have occurred sometime between 120000 and 60000 BP (Mitchell *et al*, 1973; West *et al*, 1974); however, the contradictory climatic results obtained from pollen and beetle evidence have indicated doubt over the existence of this interstadial period (Coope 1975). The Chelford interstadial has been conventionally assigned an age of 60800±1500 years BP (Mitchell *et al*, 1973), based on isotopically enriched radiocarbon date (GrN-1475) on a thin peat horizon (Vogel & Zagwin 1967). There is considerable doubt about the validity of this ^{14}C date. Other ^{14}C determinations on Chelford material have yielded ages between 26000 years BP and infinity (Worsely 1980), and recently the Chelford interstadial has been thought to be a correlative of stage 5a of the deep sea oxygen isotope record (Worsely *pers.comm.*), although the evidence for this is not yet published.

Interstadial deposits at Brimpton have on biostratigraphical grounds been assigned an age younger than the Chelford but older than the Upton Warren interstadial (45000 bp) (Bryant *et al*, 1983a). As with the Chelford interglacial list the results of all the biological evidence are consistent with a short period of climatic amelioration.

The Upton Warren interstadial is mainly based on thermophilous coleoptera assemblages (Coope 1975). Despite the absence of palynological evidence for the presence of arboreal vegetation, thermophilous herb assemblages are known from the Upton Warren type site (Coope *et al*, 1961).

Examination of the contained pollen from interbedded silt layers in gravel terraces in Surrey has indicated the presence of as yet unnamed interstadial younger than the Upton Warren (Gibbard *et al* 1986; Bryant *et al* 1983a). This interstadial has been assigned an age of around 36000 years BP on the basis of radiocarbon dates from two sites, although thermoluminescence dating of associated silts yielded ages of 106000±11000 and 107000±15000 years BP (Southgate 1984; Gibbard *et al* 1986).

The Speleothem Growth Record and the UK Quaternary Stratigraphy

The discrepancy between the number of speleothem growth peaks (9) in the upper Pleistocene and the number of recognised interstadial and interglacial periods (6) indicates that the UK Quaternary stratigraphy needs to be examined in the light of the results of absolute dating methods.

The Middle Pleistocene Record

The earliest finite U-series dates from Britain associated with material of Quaternary significance are from Pontnewydd Cave in Wales, where a debris flow deposit (the lower breccia) contains hominid and other faunal material.Examination of hominid molars has shown the presence of robust roots, taurodentism and other features consistent with a Neanderthal-like species of *Homo sapiens* (Stringer 1984). The other mammalian faunal remains are consistent with an open steppe environment and more continental climatic conditions than presently occur in the UK (Currant 1984). The fauna comprises:

Canis lupus	wolf
Ursus sp.	bear with spelaeoid characteristics
cf. Crocuta crocuta	spotted hyena
Panthera aff. pardus	a leopard-like felid
Equus sp.	horse
Dicerorhinus hemitoechus	narrow-nosed rhinoceros
D. cf. kirchbergensis	Merk's rhinoceros
Cervus elaphus	red deer
Bos or Bison sp.	a bovine
Lemmus lemmus	Norway lemming
Arvicola sp.	a water vole
Microtus gregalis	narrow-skulled vole
M. oeconomus	northern vole
Ochotona sp.	a pika

The lower breccia contains and is overlain by speleothems. 34 age determinations have been made on 16 samples by three different research groups (Schwarcz 1984; Ivanovich *et al* 1984b, and Debenham *et al* 1984); thermoluminescence dating has also been carried out on speleothem calcite (Debenham *et al* 1984). Conventional examination of the age data (Figure 3.10) has yielded confused and contradictory results (Green 1984); however construction of distributed error

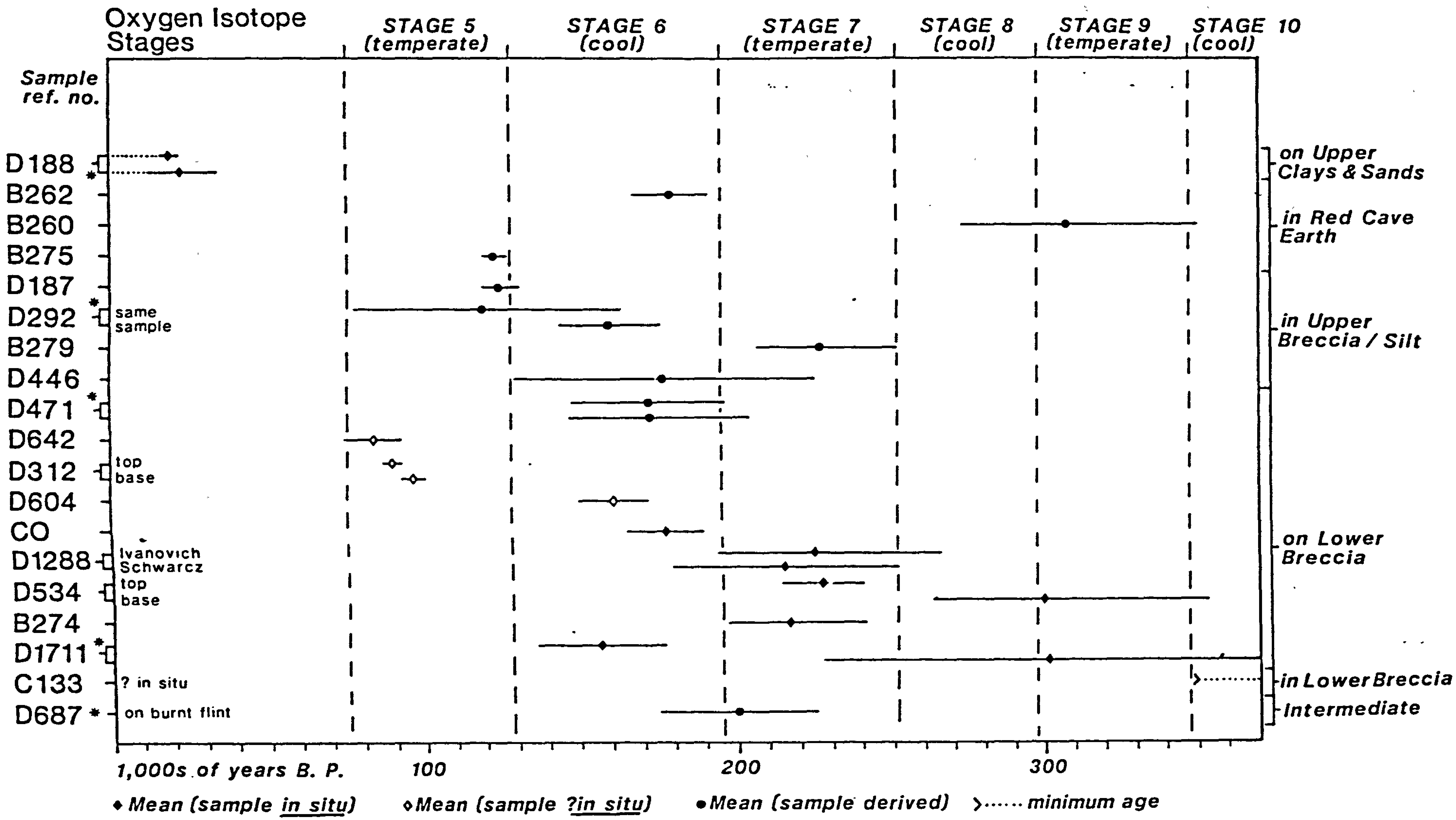


FIGURE 3.10 : PONTNEWYDD CAVE Uranium Series and Thermoluminescence* Ages (Green 1984)

weighted frequency curves from the uranium series analysis of the Pontnewydd lower breccia speleothems clearly shows the presence of three distinct periods of speleothem growth (90000, 165000 and 205000 years BP) (Figure 3.11). Since these speleothem dates come from material incorporated in the lower breccia as well as *in situ* deposits on top of the breccia, the dating indicates that the lower breccia was emplaced some time between 205000 and 165000 years BP, and that further speleothem deposition on top of the breccia occurred around 90000 years BP in some parts of the cave. Alternatively the lower breccia could have been emplaced before 205000 years BP and have two subsequent periods of deposition on top, since 10 dates of about 200000 years BP came from stalagmite floor sample D1288 on top of the lower breccia (Ivanovich *et al*, 1984).

The upper breccia and silt beds at Pontnewydd contain a mammal fauna that has a distinctly different preservation (type III) to that found in the lower breccia. This fauna indicates a marked difference in the climatic conditions compared to the lower breccia fauna. It is a classic cold fauna which is indicative of harsh climatic conditions with open, treeless vegetation and extensive seasonal snow (Currant 1984). It comprises:

Canis lupus	wolf
Vulpes vulpes	red fox
Ursus cf. arctos	brown bear
Equus ferus	horse
Rangifer tarandus	reindeer
Ovibos moschatus	musk ox
Dicrostonyx torquatus	collared lemming
Lepus cf. timidus	arctic hare

The upper breccia also contains derived speleothems and is overlain by speleothems. Five finite age determinations have been made on four samples and yielded dates of 227000 $^{+24000}_{-20000}$ years BP, 170000 $^{+33000}_{-25000}$ years BP (2 dates) and 124000±5000 years BP (2 dates).

Considering the stratigraphy of these speleothems it is possible that the upper breccia was either deposited between 170000 and 124000

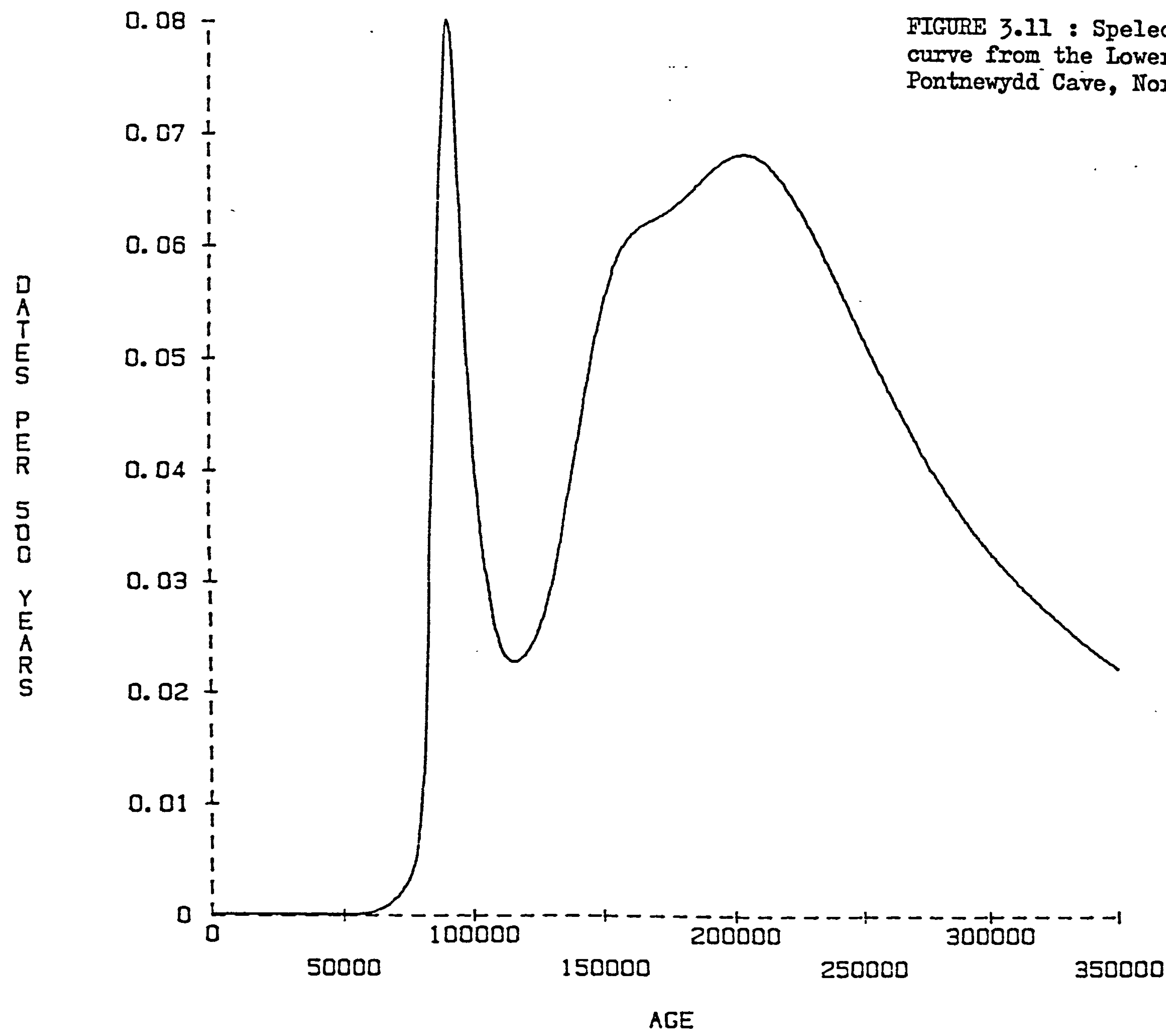


FIGURE 3.11 : Speleothem age frequency curve from the Lower Breccia of Pontnewydd Cave, North Wales.

years BP or more probably some time after 124000 years BP.

Active speleothem deposition occurred at Pontnewydd Cave during 4 main periods: 205000 years BP, 165000 years BP (which may correlate with the pre-Ipswichian 1 peak of the UK record), 125000 years BP (which correlates with the Ip 3 peak 124000 years BP) and 90000 years ago (which correlates with the Ip 1 peak 90500 years BP). Stable isotope analyses of stalagmite D312 which probably grew *in situ* on the lower breccia indicates warm climatic conditions between 96000 and 88000 years BP were followed by a rapid cooling around 87000 years BP. This is consistent with the best estimate high resolution UK speleothem growth record (Figure 3.7 & Table 3.4).

At Marsworth, Bucks, 5 age determinations have been made on a derived travertine block within the lower channel deposits. The travertine contains mollusca indicative of warm interglacial conditions, eg *Azeca goodalli*, *Discus rotundatus*, *Clausilia bidertata*, and also bears leaf impressions of temperate woodland species including *Acer* (Maple) Green *et al* (1984). The lower channel contained a mammalian fauna that is biostratigraphically post Cromerian but not of Hoxnian or Ipswichian age and can be correlated with other faunas of 'Ilfordian Age' (see chapter VI). The fauna consists of:

Canis lupus	wolf
Ursus arctos	brown bear
Panthera leo	lion
Mammuthus primigenius	mammoth
Equus ferus	horse
Equus hydruntinus	extinct horse
Cervid	a deer
Bovini	a bovid
Microtus oeconomus	root vole

Of the 5 uranium series analyses, 2 have $^{230}Th/^{234}U$ ratios greater than 1 and are unusable. Of the 3 finite dates 2 had $^{230}Th/^{232}Th$ ratios less than 20, indicating detrital thorium contamination. Only 1 yielded a useable date of 149000 $^{+16000}_{-14000}$ years BP. This would correlate it with the Men 8 peak (150000 years BP) of the Mendip speleothem growth record. However, considering the problems encountered with dating the Marsworth travertine, this dating is extremely tentative.

The Upper Pleistocene Interglacial Record

UK deposits of Upper Pleistocene age have been much more securely dated by the uranium series method than those of middle Pleistocene age. Sediments correlated with the Ipswichian *sensu lato* have been dated at Victoria Cave, northwest Yorkshire (Gascoyne *et al* 1981, 1983c). Speleothem was found in association with a typical 'hippopotamus fauna' which is similar to faunas described by Sutcliffe & Kowalsky (1976) as highly characteristic of Ipswichian deposits. The fauna is indicative of warm interglacial conditions and has been correlated with the warmest part of the Ipswichian-Eemian interglacial (Sutcliffe 1960). It comprises:

Ursus arctos	brown bear
Crocuta crocuta	spotted hyaena
Panthera leo	lion
Palaeoloxodon antiquus	straight tusked elephant
Dicerorhinus hemitoechus	narrow nosed rhinoceros
Hippopotamus amphibius	hippopotamus
Megaceros giganteus	giant deer
Cervus elaphus	red deer
Bos or Bison sp.	a bovine

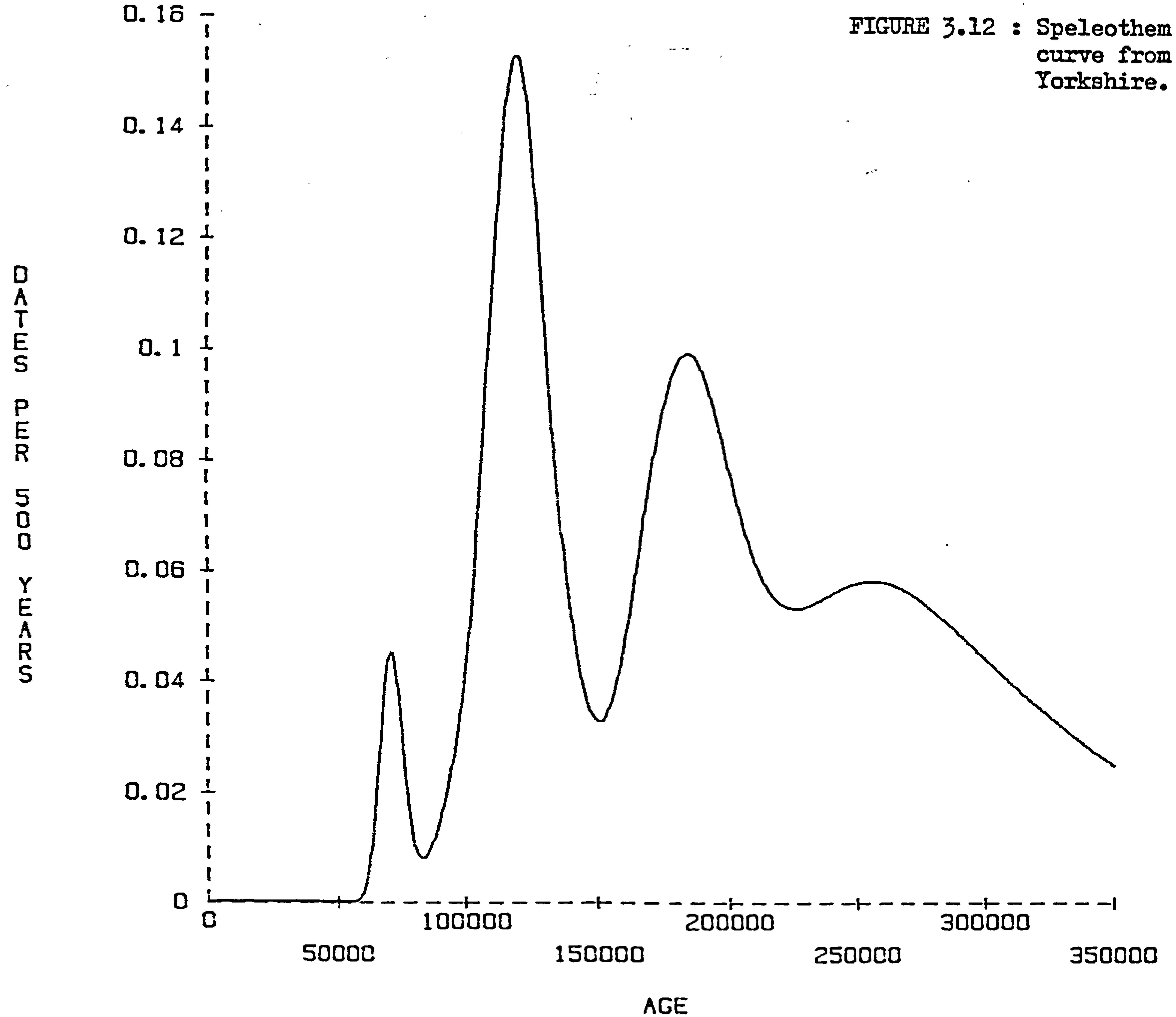
Seven samples of speleothem from the Piggard Museum, Settle, that contained faunal remains have been analysed and yielded eight reliable ages. These ranged from 135000 $^{+9000}_{-8000}$ years BP to 114000±5000 years BP with a mean of 125000 years BP. The classic Ipswichian interglacial 'hippopotamus fauna' is clearly correlated with the Ip 3 peak (124000 years BP) of the speleothem record and, as recognised by Gascoyne *et al*, with isotope stage 5e of the deep sea record.

Analysis of all the uranium series age determinations from Victoria Cave has indicated the presence of 4 main periods of speleothem deposition centred at 256000 years BP, 180000 years BP, 123000 years BP and 72000 years BP (Figure 3.12). The latter three speleothem growth periods clearly correlate with peaks pre Ip 1 (180000 years BP), Ip 3 (124000 years BP) and Dev 6 (76000 years BP).

An interglacial molluscan and vertebrate fauna associated with speleothem has been reported from Bacon Hole, Gower (Stringer 1975, 1977; Stringer *et al* 1984, 1986). Here two vertebrate faunas of interglacial character are separated by deposits that contain a cold fauna. These fauna are generally similar to the 'hippopotamus faunas' of 'Ipswichian' age in Joint Mitnor and Victoria Cave, but remains of *Hippopotamus amphibius* are absent. The lower interglacial fauna is associated with broken blocks of stalagmite that predate the deposits. Five age determinations have been made on two samples. Three of these analyses were heavily contaminated by detrital thorium whilst the remaining two dates are 124000±16000 years BP and 122000±11000 years BP. This fauna can probably be correlated with Ip 3 or, if a hiatus is present, with Ip 2 (105000 years BP). The upper interglacial fauna is capped by a speleothem dated to 81000±18 years BP. The fauna must therefore be associated with the Dev 6 (76000 years BP) or more probably the Ip 1 peak (90500 years BP). More precise analyses of this upper speleothem will hopefully resolve this problem in the future (see Appendix 1). The Bacon Hole deposits provide fairly conclusive evidence for the existence of more than one interglacial period in the UK during the upper Pleistocene (Stringer *et al* 1986).

Preliminary work at Minchin Hole, Gower, has indicated that the 'Patella beach' is older than 10100±10000 years BP (Sutcliffe & Currant 1984). Five analyses have been carried out on a fallen stalagmite block that lies on top of the 'Patella beach' and within the 'Neritoidies beach'. Unfortunately four of these determinations were contaminated by detrital thorium. The vertebrate fauna of the

FIGURE 3.12 : Speleothem age frequency curve from Victoria Cave, Yorkshire.



'Neritoidies beach' and the overlying earthy breccias is interglacial in character and suggests the presence of temperate deciduous forest. The fauna consists of:

Crocuta crocuta	spotted hyaena
Panthera leo	lion
Ursus sp.	a bear
Dicerorhinus hemitoechus	narrow nosed rhinoceros
Cervus elaphus	red deer
Dama dama	fallow deer
Sus scrofa	wild boar
Microtus agrestis	field vole
Apodemus sylvaticus	wood mouse

The Minchin Hole data provide further evidence for a post 'Ipswichian' interglacial in Britain. The fauna probably correlate either with the Ip 2 peak (105000 years BP) or the Ip 1 peak (90500 years BP). Additional work is being undertaken to more accurately date this fauna (P Smart *pers.comm.*)

This review of the uranium series dated evidence of interglacial faunal deposits shows good agreement between the faunal evidence and the speleothem growth period results for the UK. The identification of three speleothem growth periods between 80-130000 years BP has allowed the precise dating of three UK Upper Pleistocene interglacials; and the potential correlation of these interglacials with the long core palynological records from continental Europe and with the three oxygen isotope peaks from stage 5 of the deep sea cores (see Chapter IV). This is the first time that three Upper Pleistocene interglacials have been recognised from terrestrial deposits in Britain.

The Devensian Record

Evidence suggesting that the age of the interglacial/glacial boundary lies between 80-90000 years BP comes from Stump Cross Cave in Yorkshire. Here, a single fauna indicative of cold stadial conditions has been found associated with speleothem (Sutcliffe *et al*

1985). The fauna consists of

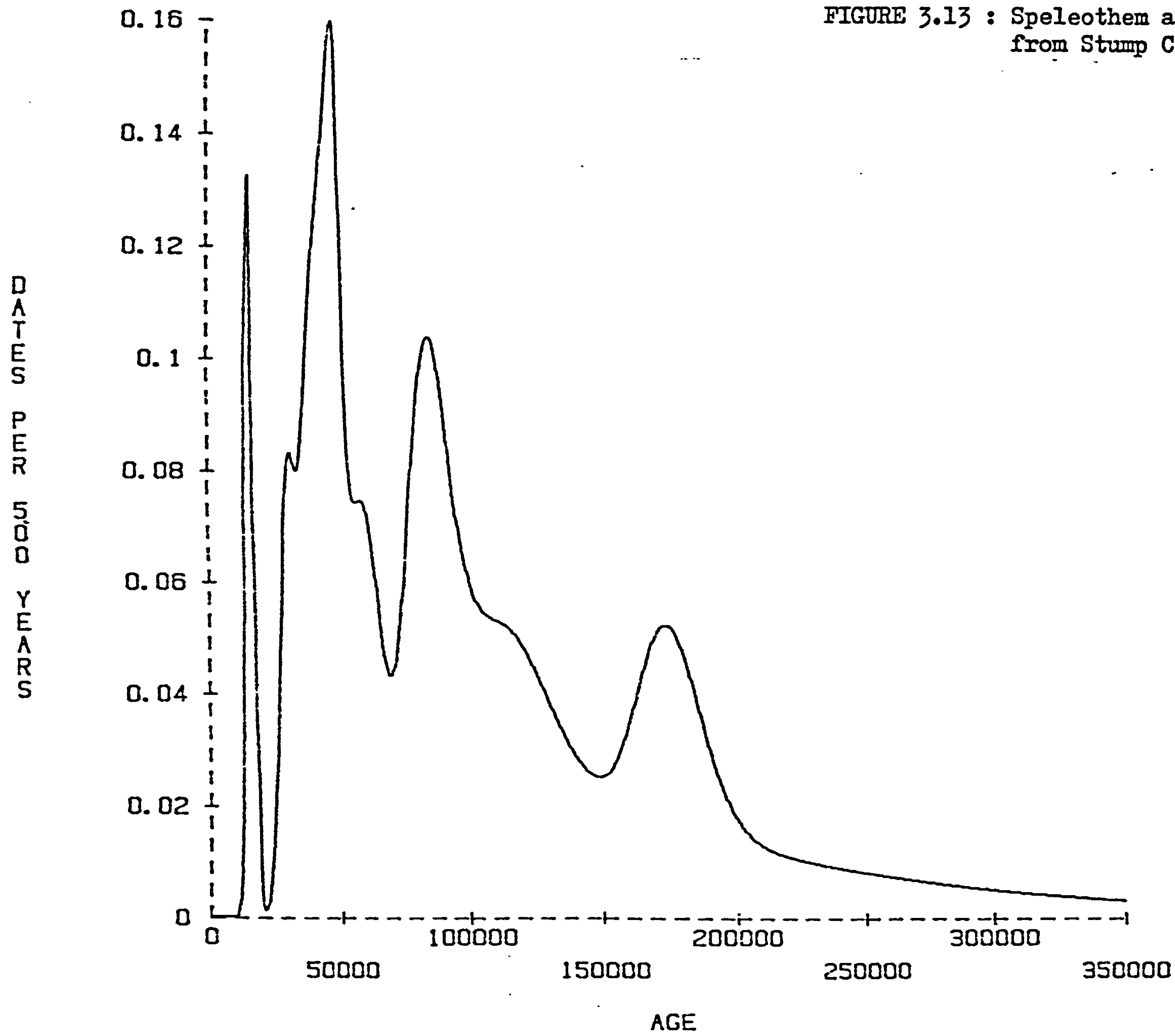
Gulo gulo	wolverine
Rangifer tarandus	reindeer
Canis Lupus	wolf
Vulpes or Alopex sp.	red or arctic fox
Bison sp.	a bovine

Thirty two uranium series analyses have been carried out on 19 samples. Speleothems beneath the main bone deposits have yielded ages in the range of 108000±18000 years BP to 118000±12000 years BP, whilst four dates on flowstone encrusting bone yielded a mean age of 83600 years BP (Sutcliffe *et al* 1985). This cold faunal assemblage clearly lies between the Ip 1 (90000 years BP) and Dev 6 (76000 years BP) peaks, and confirms the results of the isotopic studies on stalagmite D312 (see above) that the glacial/interglacial boundary in the UK lies between 80000 and 90000 years BP.

Distributed error weighted frequency curve analyses of the speleothem data of Stump Cross shows the presence of seven periods of speleothem growth (173000 years BP, 110000 years BP, 85000 years BP, 57500 years BP, 46000 years BP, 30000 years BP and 15000 years BP) (Figure 3.13). Although some of these periods correlate with the speleothem growth record in other parts of the UK, clearly local ground water conditions have allowed speleothem growth to occur at Stump Cross during periods when it is absent from other British sites.

Many of the speleothem growth periods recorded from Stump Cross Cave are anomalous when compared to both the UK record as a whole and to the record from other Yorkshire caves. Figure 3.14 shows the distributed error weighted frequency curve of 45 reliable uranium series analyses from Lancaster Hole, Yorkshire (Gascoyne *et al* 1983c). This cave has been studied for purely geomorphological purposes and 8 Pleistocene speleothem growth peaks are resolvable, eg 35500 years BP, 44000 years BP, 56000 years BP, 74000 years BP, 88000 years BP, 105000 years BP, 125000 years BP and 243000 years BP. All these growth periods are in close agreement with those from the rest

FIGURE 3.13 : Speleothem age frequency curve from Stump Cross Cave, Yorkshire.



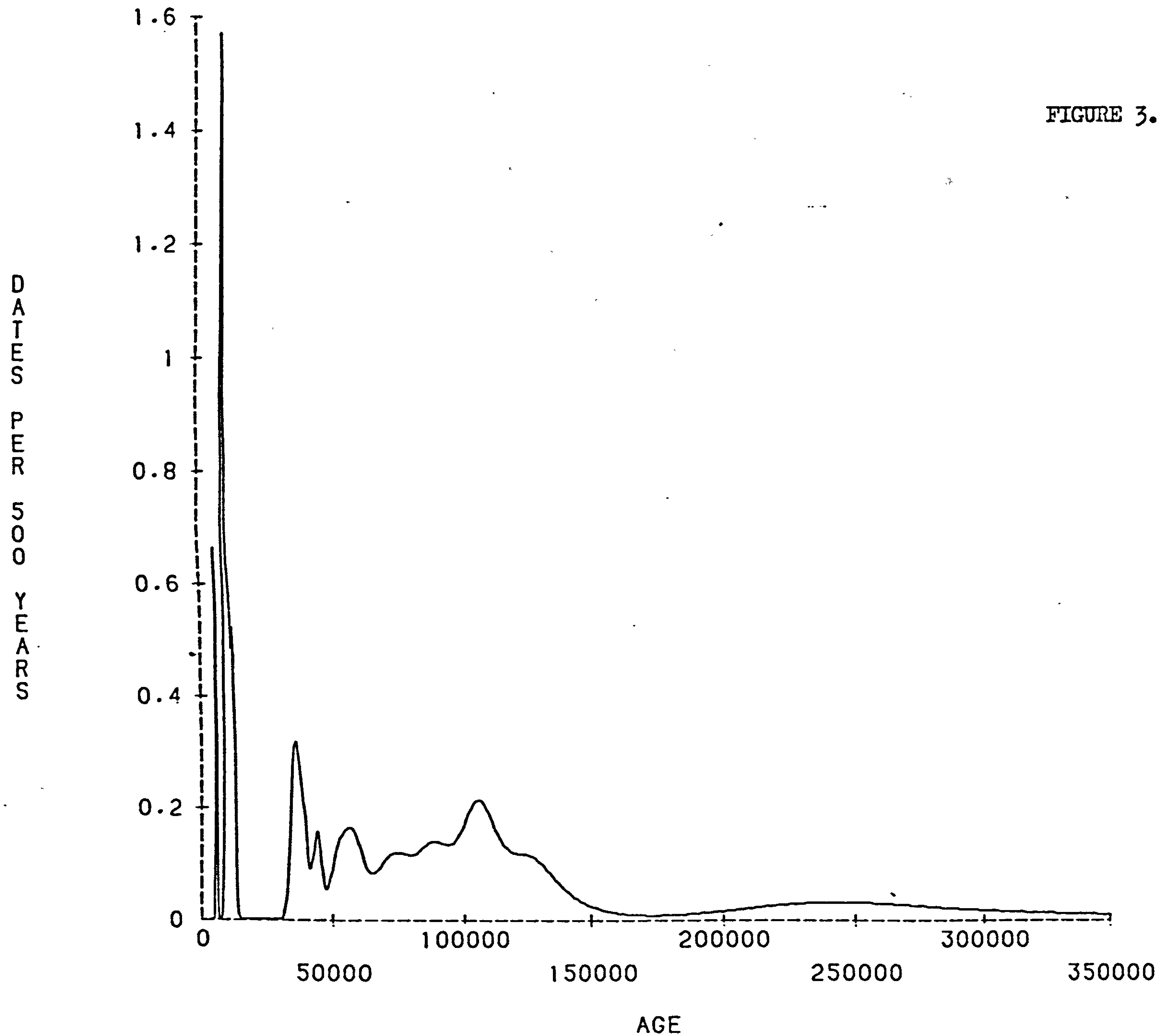


FIGURE 3.14 : Speleothem age frequency curve from Lancaster Hole, Yorkshire.

of the UK. The results from Lancaster Hole and Victoria Cave indicate that the presence of active speleothem deposition in Stump Cross cave, Yorkshire, during periods of presumed stadial conditions is an extremely local phenomenon, probably restricted to Stump Cross Cave.

Sedimentological and palynological evidence for interstadial conditions has been found in deposits from Mosedale, Cumbria (Boardman *et al* 1981). Uranium series analyses have been carried out on peat and wood samples from this deposit (see appendix 1). Although there are problems with these analyses the corrected age of 77000^{+13000}_{-11000} years BP on the 6524 (wood sample) would correlate these deposits with the Dev 6 speleothem growth peak. Until further dating is done from this site and more is known about the uranium series dating of peat deposits, this correlation should be considered tentative.

Despite the large number of speleothem dates (80) that fall between 20 and 70000 years BP in the UK record, none are usefully associated with fossiliferous material. Four major periods of speleothem deposition are evident: Dev 5 (57000 years BP), Dev 4 (50000 years BP), Dev 3 (45000 years BP), Dev 2 (36000 years BP), with an additional minor peak, Dev 1 (29500 years BP). Although it is tempting to try and correlate these speleothem growth periods with specific Devensian interstadials (for example the 45000 year peak with the Upon Warren interstadial which has been ^{14}C dated to circa. 45000 years), any attempt to do this using current evidence would be spurious. The UK Devensian interstadials have been dated solely on the basis of ^{14}C dates and despite the high precision of the ^{14}C method its accuracy is largely unknown beyond 8000 years BP due to fluctuations in the rate of ^{14}C production in the upper atmosphere (Burleigh 1975; Fletcher 1975; Suess 1979). Comparisons of the ^{14}C timescale beyond 10000 years BP with other dating methods led Stuiver (1978) to argue that the radiocarbon timescale has only deviated from an absolute chronology by a maximum of 2000 years over the past 32000 years BP. However, more recent evidence suggests greater divergences during a number of different periods (Barbetti 1980; Vogel 1980). Considering this known divergence of ^{14}C and uranium series dates of Devensian age, the only method of correlating the interstadial deposits with the speleothem peaks would be by 'counting down from the top'. Although this method has been used by others, for example Kukla (1977) to correlate terrestrial and marine deposits, the method is of dubious validity. The possibility of doing this correctly is also reduced by the presence of more speleothem peaks than recognised interstadial periods.

The Periglacial Record

Periods of low or zero speleothem growth probably indicate cold and/or arid conditions. Unfortunately the distributed error weighted frequency curve method is not ideal for precisely determining the age of these periods, since the number and precision of the dates used for constructing the peaks affects the position of the troughs. The absence of speleothem growth is thus more difficult to determine than its presence. Despite these problems the troughs in the speleothem growth curves should broadly correlate with the ages of periglacial and cold climate deposits.

There are no uranium series analyses from unambiguous glacial or periglacial sediments in the UK, although attempts at thermoluminescence dating (TL) have been made (Table 3.7). Thermoluminescence dating is a relatively new technique, with many outstanding problems, and age determination results should be treated with caution (Wintle & Huntley 1982). Several TL dates from British Devensian deposits are thought to be incorrect (Southgate 1984; Wintle & Catt 1985; Gibbard *et al* 1986). However, a reliable date of 17500±1600 years BP has been obtained from chalky solifluction deposits at Eppleworth in Yorkshire (Wintle & Catt 1985), which have been correlated with Dimlington stadial deposits (Madgett & Catt 1978;

TABLE 3.7 : COMPARISON OF UK SPELEOTHEM GROWTH PERIODS & TL DATED PERIGLACIAL DEPOSITS

Peak designation	Best estimate of peak centre age	TL date of periglacial deposit	Location	Source
Holocene Peak	10000			
		14500-18900	Britain	Wintle 1981
		17500±1600	Britain	Wintle & Catt 1985
		24000±3000	Denmark	Kolstrup & Mejdahl 1986
DEV 1	29500			
DEV 2	36000			
		39500±5000	Denmark	Kolstrup & Mejdahl 1986
DEV 3	45000			
DEV 4	50000			
DEV 5	57000			
		75000±6500	France	Wintle et al 1984
DEV 6	76000			
		80000±7000	France	Wintle et al 1984
IP 1	90500			
IP 2	103500			
		114000±16000	Britain	Holyoak & Preace 1985
IP 3	124000			
		125000±11000	France	Wintle et al 1984
		139000±12000	France	Wintle et al 1984
PRE-IP 1	180000			

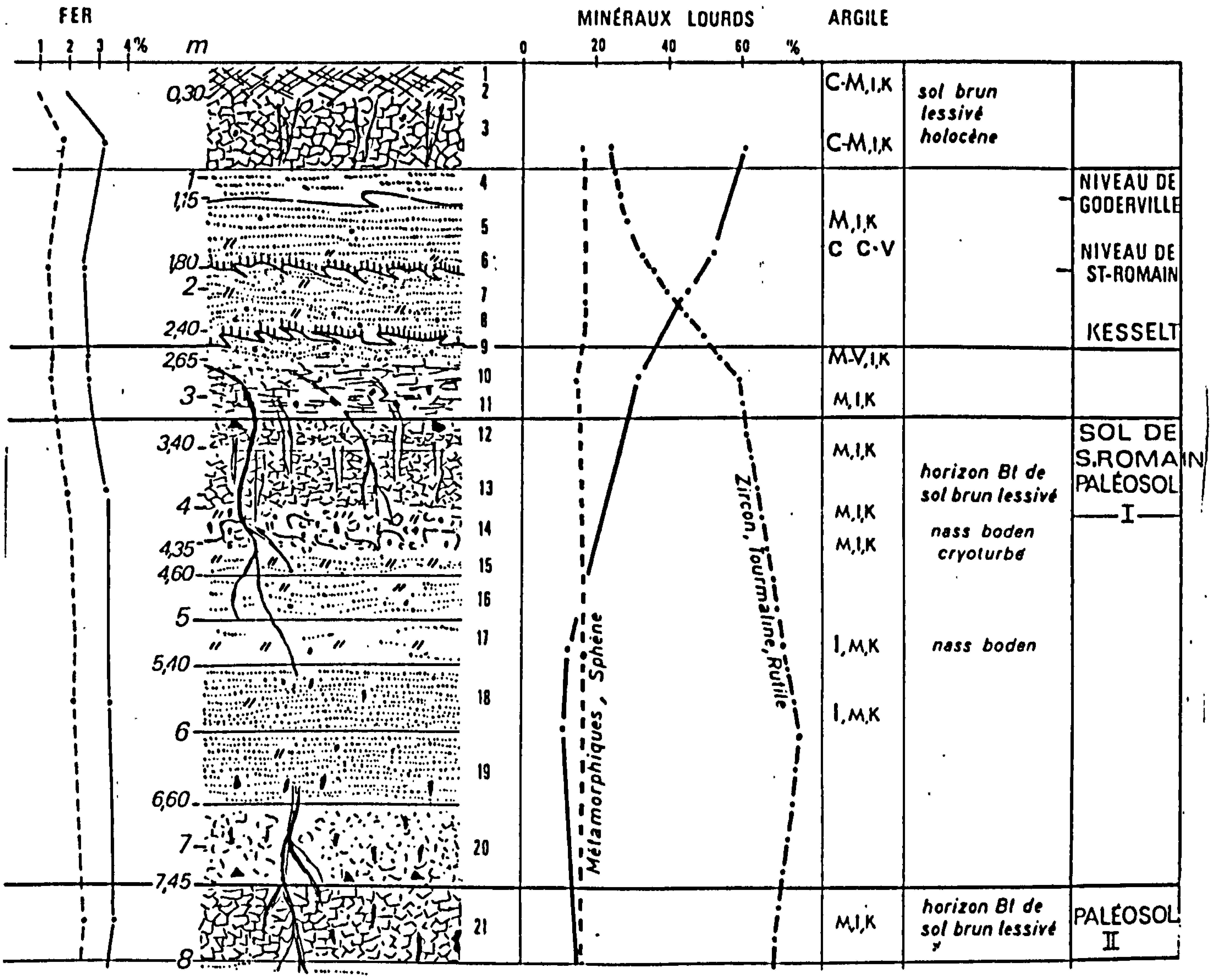
Rose 1985). Six dates of between 14500 and 18400 years BP have been obtained from aeolian loess deposits in Kent, the New Forest (2 dates), the Scilly Isles (2 dates) and Cornwall (Wintle 1981). These TL dates all fall within the region of minimum speleothem growth recorded between the Dev 1 peak (29500 years BP) and the first Holocene peak (9500 years BP). It seems probable that this trough is of Dimlington stadial age (Rose 1985).

Periglacial conditions were also occurring in Europe during the Dimlington stadial period - three frost wedge casts from Jutland in Denmark have TL ages of 17000±3000 years BP, 24000±3000 years BP and 39000±5000 years BP (Kolstrup & Mejdahl 1986). This latter date provides evidence for the occurrence of periglacial conditions in Europe between the Dev 3 peak (45000 years BP) and the Dev 2 peak (36000 years BP).

TL dating has been carried out on the top 4.5m of the Saint-Romain loess sequence in Normandy, France (Wintle *et al* 1984). Six dates between 0.3m and 1.78m on loess beneath a Holocene soil yielded ages between 11100±1000 years BP and 16400±1500 years BP, although several of these dates are stratigraphically inverted (Figure 3.15 and Table 3.7). Two loess samples from 1.82 and 2.1m which yielded ages of 75000±6500 and 80000±7000 respectively are from the Kesselt soil level which is an interstadial soil horizon with solifluction tongues (Lautridou 1968, 1982). These dates indicate that the loess in which the soil was formed was deposited in the period between the Ip 1 peak (90500 years BP) and the Dev 6 peak (76000 years BP) and therefore probably correlates with the cold fauna at Stump Cross Cave in Yorkshire. The soil then formed over the intervening interstadial periods (Dev 6 to Dev 1).

Three samples from the 'early Weichselian loam' (2.4 to 3.0 metres) yielded stratigraphically inverted ages between 88000±8000 years BP and 83000±7000 years BP, as did three samples from the 'interglacial Saint-Romain soil' (3.3-3.9m), with ages between

FIGURE 3.15 : Saint Romain stratigraphy, Normandy, France. (Lautridou 1982)



Thermoluminescence results and radioactivity data for Saint-Romain

Depth	No.	Bulk α-count rate (ks^{-1} cm^{-2})	Th (p.p.m.)	U (p.p.m.)	Sealed / Unsealed	K_2O (%)	Dose rate (mGy yr^{-1})	ED ± σ (Gy)	Age (kyr)
30	a	0.744 ± 0.018	6.4 ± 1.4	4.4 ± 0.4	1.02	1.96 ± 0.01	3.91	49.3 ± 3.5	12.6 ± 1.3
60	b	0.805 ± 0.017	10.1 ± 3.8	3.8 ± 0.5	0.96	1.88 ± 0.005	4.04	58.5 ± 2.1	14.4 ± 1.3
90	c	0.947 ± 0.015	10.6 ± 1.4	4.8 ± 0.4	1.03	1.81 ± 0.009	4.45	61.2 ± 1.6	13.7 ± 1.2
120	d	0.931 ± 0.013	9.9 ± 1.3	4.9 ± 0.4	1.09	1.81 ± 0.005	4.39	62.4 ± 2.0	14.2 ± 1.3
150	e	0.759 ± 0.013	9.5 ± 1.2	3.6 ± 0.4	1.02	1.80 ± 0.005	3.84	42.7 ± 1.6	11.1 ± 1.0
178	f	0.862 ± 0.012	11.3 ± 1.1	3.9 ± 0.4	1.01	1.77 ± 0.02	4.15	68.1 ± 2.6	16.4 ± 1.5
182	g	0.693 ± 0.011	11.3 ± 1.2	2.5 ± 0.4	1.03	1.47 ± 0.01	3.39	254 ± 1.0	75 ± 6.5
210	h	0.743 ± 0.014	9.6 ± 1.4	3.4 ± 0.4	0.97	1.50 ± 0.01	3.57	288 ± 5.0	80 ± 7
240	i	0.717 ± 0.016	9.0 ± 1.5	3.4 ± 0.5	0.87	1.46 ± 0.005	3.46	307 ± 2.0	88 ± 8
270	j	0.828 ± 0.018	9.6 ± 1.7	4.1 ± 0.5	0.95	1.45 ± 0.005	3.81	329 ± 1.9	86 ± 8
300	k	0.813 ± 0.018	9.8 ± 1.7	3.9 ± 0.5	0.96	1.61 ± 0.01	3.88	323 ± 4.0	83 ± 7
330	l	0.736 ± 0.016	8.9 ± 1.6	3.5 ± 0.5	0.97	1.69 ± 0.01	3.69	442 ± 2.0	120 ± 10
360	m	0.764 ± 0.017	7.2 ± 1.5	4.3 ± 0.5	0.91	1.71 ± 0.007	3.79	420 ± 4.0	111 ± 10
390	n	0.702 ± 0.015	7.7 ± 1.4	3.6 ± 0.4	0.98	1.65 ± 0.01	3.55	407 ± 11	114 ± 10
420	o	0.726 ± 0.012	7.4 ± 1.0	3.9 ± 0.3	1.10	1.68 ± 0.007	3.65	457 ± 19	125 ± 11
450	p	0.626 ± 0.012	7.8 ± 1.2	3.0 ± 0.4	1.03	1.67 ± 0.01	3.32	462 ± 16	139 ± 12

120000±19000 and 110000±10000 years BP (Lautridou 1982, Wintle *et al* 1984). Therefore, the ages of these two units should only be taken as tentative. Lastly, dates of 125000±11000 years BP (4.2 metres) and 139000±12000 years BP (4.5 metres) were obtained from the nearly cryoturbated 'Saalian' loess beneath the interglacial Saint-Romain soil (Wintle *et al* 1984). This loess clearly correlates with the period of markedly reduced speleothem growth that predates the Ip 3 peak (124000 years BP).

Holyoak & Preece (1985) have obtained a TL date of 114000±16000 years BP from the basal calcareous silts at Tattershall Castle, Lincolnshire, which contain a molluscan assemblage characteristic of open country environments. This date falls between the IP-3 (124000 years BP) and IP-2 (103500 years BP) peaks. The basal silts are overlain by fossiliferous interglacial deposits which have been correlated with Ipswichian substage IP IIb on the basis of their contained pollen which showed a dominance of "oak forest pollen with appreciable frequencies of Alnus and Corylus". The TL date makes it unlikely that these interglacial pollen spectra relates to the IP-3 peak (124000 years BP) and provides further evidence of post Ip-3 interglacials and the confused status of the upper Pleistocene interglacial pollen record in the UK.

Comparisons of TL dated periglacial deposits in Britain, France and Denmark shows excellent agreement with the ages of four of the low speleothem growth periods in the UK (Table 3.6). This provides strong support for the idea that speleothem growth in Britain mainly occurred during interstadials and interglacials and virtually ceased during stadial periods.

Speleothem Growth : The World Record

Since the first uranium series data of cave calcite deposits were published in 1962 (Rosholt & Antal), around one hundred uranium series dating laboratories have been set up and produced dates. Unfortunately no periodical similar to Radiocarbon exists for the rapid publication of these dates, so most are as yet unpublished. The uranium series literature is also widely scattered in several different languages and since there is no accepted standard format for quoting uranium series analyses, the data are often incomplete. Figure 3.16 gives a rough idea of the geographical distribution of uranium series dated speleothem and travertine deposits. It has been compiled from the published literature and is therefore almost certainly incomplete. The distribution is plotted on a Peter's projection of the world which is an equal area projection and so gives a more accurate estimate of the spatial coverage of the uranium series data than would the more common Winkel or Mercator projections. The majority of the uranium series dating laboratories are located in Europe and North America and so likewise are most of the dated sites. Virtually no age determinations have been carried out from South American, African or Asian sites. Although there are a number of uranium dating laboratories in China and the USSR, their results have not yet reached the Western literature. The Asian coverage displayed in Figure 3.16 is probably a gross underestimate.

Considerable numbers of dates are available from polar, cooler humid and warmer humid world climatic zones, with dry and tropical humid regions having fewer dated sites (as defined by Köppen 1931). Unfortunately the number of reliable analyses published with enough information for use by the distributed error weighted frequency curve method is currently too small to attempt to determine speleothem growth periods on a global scale. It is therefore not yet possible to place the Mendip and UK records in a global context. Clumping all the speleothem age data together and analysing it as a whole would yield meaningless results as the effects of Quaternary climatic changes upon speleothem growth rates vary from region to region. For example, increased rainfall during glacial periods led to increased speleothem growth and travertine deposition in areas of Israel that are currently semi-arid (Schwarcz *et al* 1980).

FIGURE 3.16 : World distribution of dated speleothems and travetines.

Preliminary work on tropical and semi-tropical speleothem data has also indicated that speleothem growth occurred during periods of glacial conditions in the UK. These examples demonstrate that the division of the world into just two climatic zones (tropical and non-tropical) as proposed by Hennig *et al* 1983, is over-simplistic for reliably determining speleothem growth records on a global scale.

The North American record

The problems discussed in the last section can be illustrated by examining the North American speleothem record. 171 finite uranium series age determinations are available for analysis and their geographical distribution is shown in Figure 3.17 and Table 3.8. Examination of the distributed error weighted frequency curve for these data show a complex and confused picture containing a large number of closely spaced peaks (Figure 3.18). Stripping the curve by the removal of imprecise age determinations just results in even more closely spaced peaks being resolved (16). The presence and positioning of these peaks makes little geological sense and indicates that the effects of Quaternary climatic fluctuations or speleothem growth varied in different regions of North America. This is unsurprising considering the large climatic differences which currently exist between these sites. The Nahani, British Columbia, Quebec, and Utah sites all currently fall within sub-arctic or tundra climatic zones of the Köppen (1931) classification system, whereas the Minnesota, West Virginia and Kentucky sites all have continental climates, the Arkansas site a humid sub-tropical climate and the New Mexico site a desert climate. It seems probable that speleothem growth sites would have been different in these different regions throughout the Quaternary as they are today, and that the effects of Quaternary climatic fluctuations would be region dependent. Comparison of the uranium series data from the sub-arctic climatic sites with that from the continental climatic sites indicates that

TABLE 3.17 : Distribution of dated speleothems in North America.

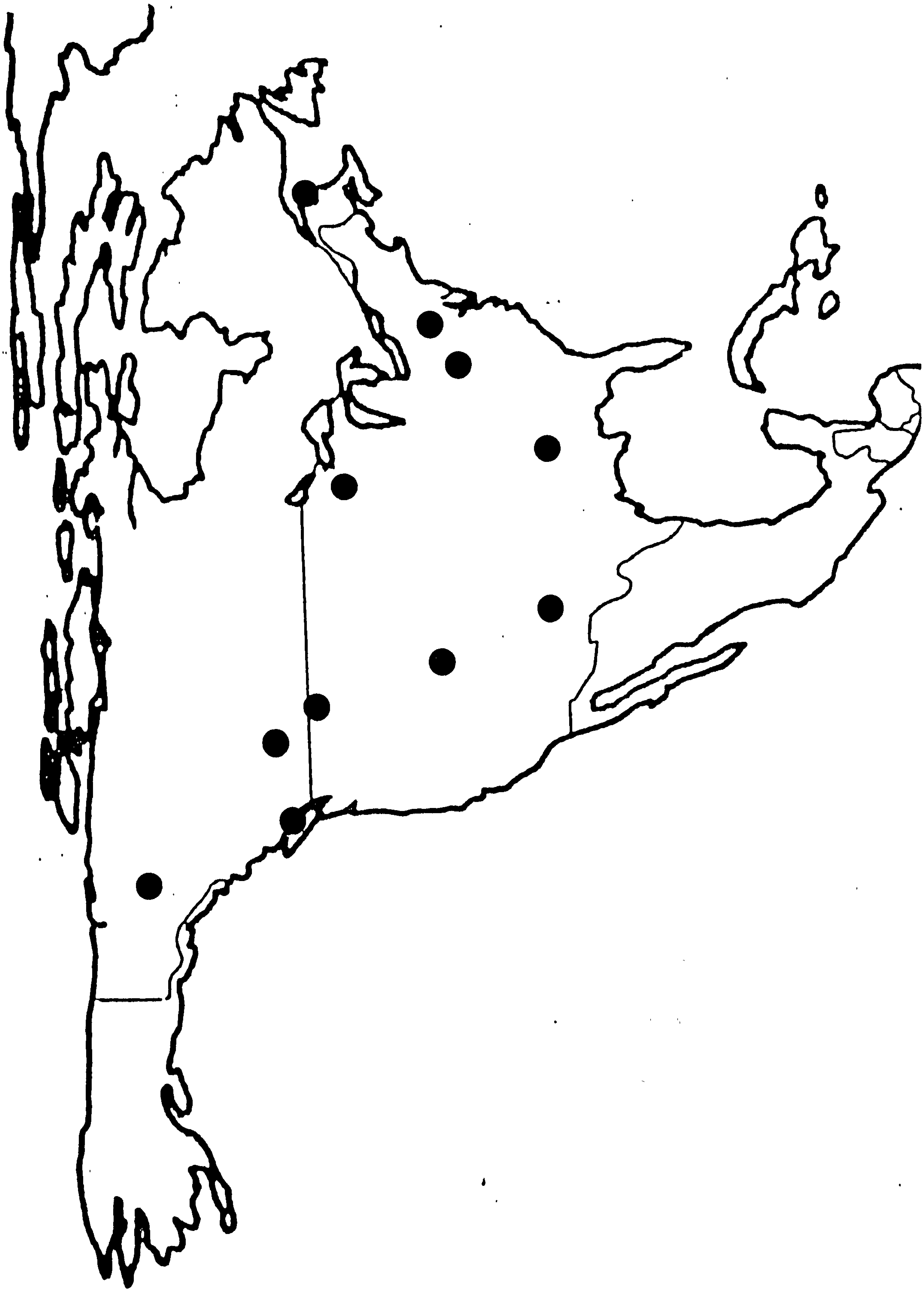
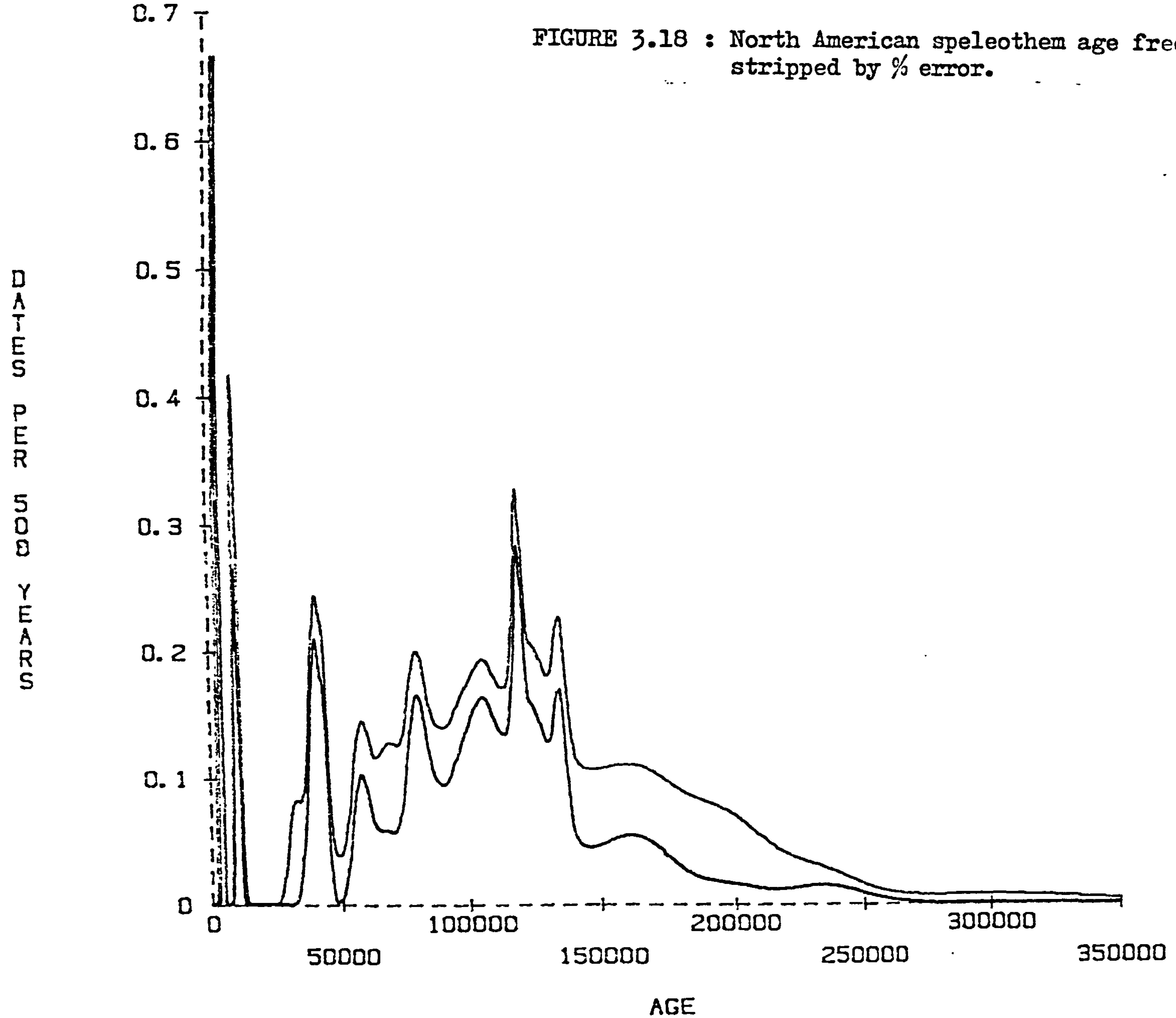


TABLE 3.8 : NORTH AMERICAN SPELEOTHEM DATA (* = Not all data quoted in published results)

Region	No. of sites	Reliable analyses	Unreliable analyses	Source
Nahani Plateaux NW Territory Canada	6	15	1	Harmon et al, 1977
Columbia Icefield British Columbia Canada	1	14	1	Harmon et al, 1977 Gascoyne et al, 1983a
Crows Nest Pass British Columbia Canada	5	8	2	Harmon et al, 1977
Vancouver Island Canada	1	7	20	Gascoyne et al, 1986 Latham et al, 1982
Gaspesie Quebec Canada	1	0	6*	Roberge & Gascoyne 1978
Bear River Range Utah USA	2	3	0	Harmon et al, 1977
New Mexico USA	1	2	0	Harmon & Curl, 1978
West Virginia USA	2	24	1	Thompson et al, 1975a, 1976
Arkansas USA	1	0	9*	Thompson et al, 1975
Minnesota USA	4	22	24	Lively et al, 1981
Kentucky USA	1	0	9*	Harmon et al, 1978a Hess & Harmon, 1981
	25	96	74	

FIGURE 3.18 : North American speleothem age frequency curve stripped by % error.



this is the case (Figure 3.19). There appears to be a high degree of inverse correlation between these two records with speleothem growth in the sub-arctic occurring during low growth periods in the continental sites and *vice versa*. The periods of speleothem growth in the sub-arctic broadly correspond with the UK growth periods (Marine West Coast climatic zone), although there are notable differences. These results should only be considered as highly tentative for the following reasons:

1) the number of dates used to construct these two curves is small;

2) although the two groups of sites come from broadly similar climatic zones they still span a wide range of climatic variation;

3) speleothem growth in Castleguard Cave, British Columbia, can occur by non-biogenic means (Atkinson 1983; Gascoyne & Nelson 1983b) and this will distort the biogenic growth record;

4) the division of the sites into groups based on the Köppen (1931) climatic zones may not be the optimum method. It is possible that partitioning based on a more 'ecologically' determined index such as Thornthwaite (1943) may be more accurate.

To conclude, examination of the North American speleothem growth record indicates the presence of complex inter-regional differences. The published data are not yet of a sufficient size or quality to enable these differences to be accurately defined, but there appears to be no reason why this should not be possible when more data become available.

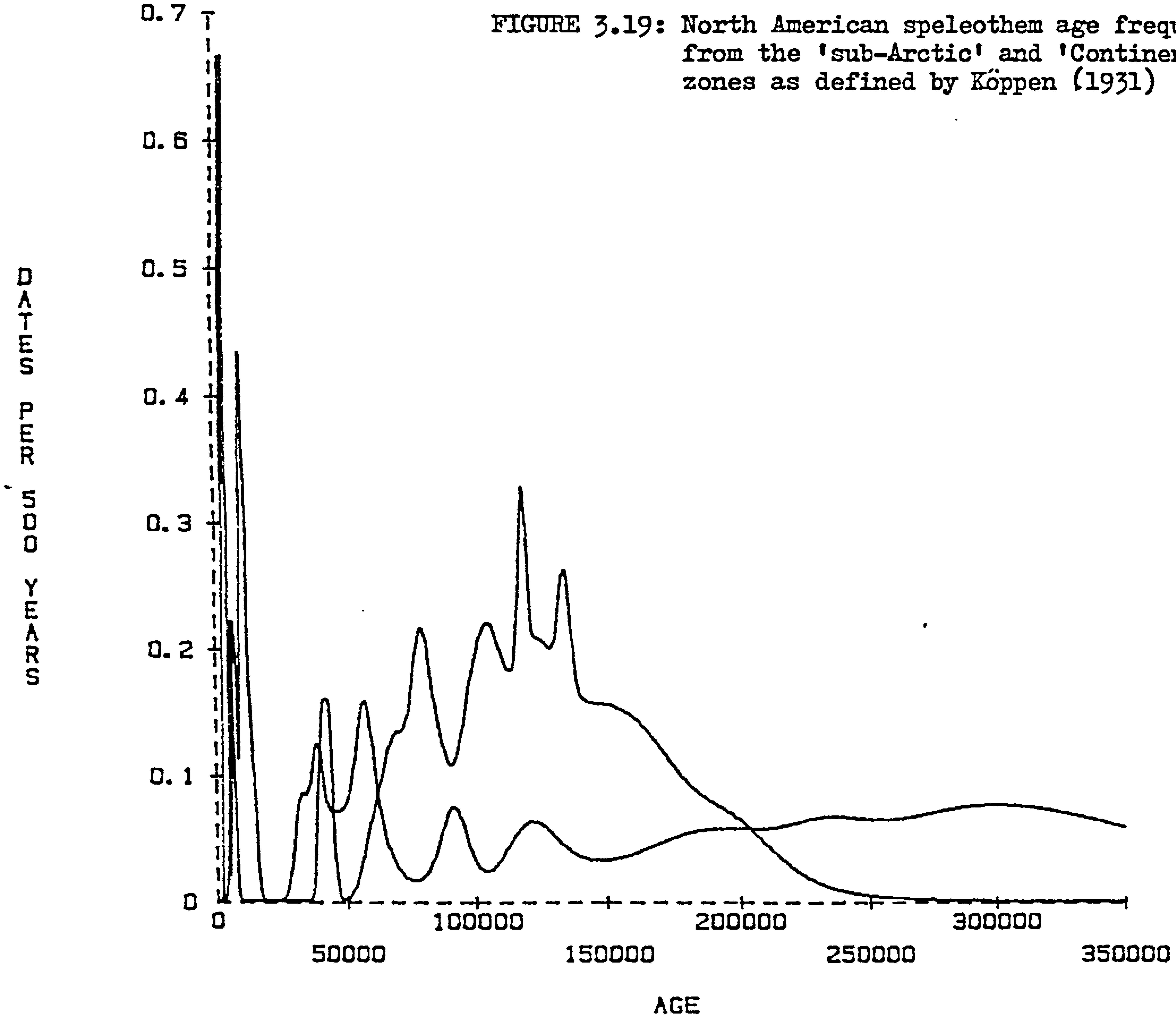


FIGURE 3.19: North American speleothem age frequency curves from the 'sub-Arctic' and 'Continental' climatic zones as defined by Köppen (1931)

Conclusions

The distributed error weighted frequency curve method of Gordon & Smart (1984) provides a method of determining the periods of speleothem growth in the Mendip region and the UK. These records are stable, internally consistent and statistically reliable and display a high level of correlation with Milankovitch forcing functions and the results of TL dating. Speleothem growth periods have been shown to correspond with interglacial and interstadial climatic conditions in the UK on both theoretical grounds and by correlation with interglacial faunas. The speleothem record thus provides a continuous absolute chronological framework for at least the upper Pleistocene, within which it is necessary to redefine the biostratigraphic and lithostratigraphic units from the Mendips, since these are currently dated by correlation with the 'conventional' UK Quaternary stratigraphy of Mitchell *et al* 1973, which has been shown to be incorrect and in need of revision.

In future it should be possible to correlate the Mendip and UK speleothem growth records with those from other regions of the world. This will increase our understanding of the effects of Quaternary climatic oscillations at the inter-regional level and may enable the correlation of time-transgressive lithostratigraphic and biostratigraphic units at an inter-regional level. Improved uranium series analysis techniques will increase both the accuracy and precision of the method (see Appendix 1) and this should enable the reliable determination of speleothem growth periods within the middle Pleistocene.

It may also become possible to distinguish between interglacial and interstadial periods on the basis of variations in peak widths and possibly peak heights, rather than by correlation with fossiliferous deposits. It would be expected that during interglacials, favourable conditions for continuous speleothem growth would occur over an extended period of about 10000 years, and these events would be recorded as broad peaks, whereas shorter interstadial events of a few thousand years' duration would be recorded as narrower peaks. If the other factors that distort the true relative widths of the peaks can be controlled, then it will be possible to measure the duration of these periods of climatic amelioration. If these periods can then be correlated with fossiliferous deposits it will be possible to test the assumption that the major difference between interstadials and interglacials is their duration rather than their climatic conditions (West 1979), and thus whether the successional model of interglacials proposed by Turner & West (1968) is valid.

C H A P T E R I V

THE MENDIPS AND WORLD SEA-LEVEL RECORDS

Over the past century a large amount of effort has been expended on the study of marine shore lines, both in the Mendip region and in many other parts of the world. The reasons for this are two-fold: firstly, the study of sea-level changes is a subject of interest in its own right, as these changes are largely determined by the amount of water that is globally locked up as ice; secondly, changes in sea-level affect the base levels of the fluvial system and so the rates and nature of erosion (Clayton 1977, Rose 1978). This will have profound effects on the geomorphology and landscape evolution of any region. Therefore, to understand and explain the evolution of the present day geomorphology of the Mendip region it is not only necessary to know the climatic changes that have occurred, but also the nature of changes in base level. This is a fundamental pre-requisite the importance of which should not be underestimated.

The influence of base level on the erosion and landscape evolution of a region by surface streams has been recognized since the work of Davis (Chorley *et al* 1973, King & Schumm 1980). However, the concept of a single regional base level which controls the nature of all fluvial activity is no longer tenable in karst areas. The Mendip aquifer is known to be anisotropic, containing vadose streams which cross one another at different levels within the limestone massif without mixing (Drew 1966; Atkinson 1971). The sub-surface hydrology therefore responds to changes in local hydraulic gradients rather than to changes in regional base levels.

The effect of sea-level changes on karstic circulation and erosion are therefore complex. This idea contrasts strongly with the simplistic assumptions made during the era of 'denudation chronology', namely that

1) caves have horizontal passages on several different levels which can be correlated regionally between caves;

2) these levels will correlate with the heights of gravel benches in surface valleys;

3) caves will mainly occur adjacent to large surface valleys;

4) cave passages decrease in size and increase in number away from the surface valleys;

5) caves form rapidly in response to water table changes.

(Sweeting 1950; Davies 1960; Woodward 1961.)

All these assumptions have been shown to be false in the Mendip region and elsewhere (Drew 1975). Unfortunately virtually all of the sea level studies in the Mendip region have been based on the idea that different features can be correlated solely on the basis of their heights (eg if it is at 20m it must be Hoxnian).

Considerable confusion exists in the Mendip literature about the heights of littoral erosion features and the number of stages of marine transgression these represent. The highest platform described is that by the Kewstoke coast road (S.T.326630) which is buried in 'head', the surface of which has been levelled at 30m O.D., with a surface relief of over 2m (Gilbertson 1974). It is interesting to note that despite extensive earlier work in the Kewstoke area, and interest in finding a '100 foot' (30.8 metres) raised beach which would correspond to the'100 foot' Severn and Avon terraces (Palmer 1931), this 'marked platform' was not recognized as having a littoral origin until the work of Gilbertson (1974).

Extensive evidence for widespread marine erosion which would correspond with the '50 foot raised beach level' (15.4 metres) was widely discussed during the nineteenth and first half of the twentieth centuries. Palmer (1931) recorded: *"The beach may be traced along the coast from just below the Pier Hotel at Portishead to Brean Down south of Weston-Super-Mare. South of this the beach runs inland to the foot of the Mendip Hills, roughly along the line taken by the present road from Bleadon to Cheddar and thence to Wookey via Draycott and Westbury."*

Additional evidence for marine erosion at a '50 foot' level was noted by many authors, although the heights they quoted often ranged between 50 and 60 feet (15.4 to 18.5 metres) - MacKintosh (1868); Greenly (1921, 1922); Palmer & Hinton (1929); Palmer (1931, 1934); Tratman (1955) and Ap Simon *et al* (1961). This '50 foot raised beach' was thought to have formed during 'the last cold epoch and probably about Mousterian times' (Palmer & Hinton 1929; Palmer 1931).

However, Gilbertson (1974) and Gilbertson & Hawkins (1974) contend that the '50 foot raised beach' does not exist in most places. Gilbertson re-levelled the 'wave-cut notch' in the cliff at Holly Lane (S.T.419727) at 20 metres O.D. and correlated this with the base of the '70 foot cliff line (21.3 metres) at Brean Down (Ap Simon *et al* 1961), the erosional 'beach' on the southern slopes of the Mendips at 21 metres O.D. (Ford & Stanton 1968), the 'fossil cliff' around Weston Old Pier by the toll booth (S.T. 311626) at 22 metres O.D. and possibly with a '70 foot platform around Worle Church (S.T. 354629) and Back Hill (S.T. 418738). Gilbertson (1974) also noted a marine erosion platform above 12 to 13 metres O.D. along the footpath at Back Hill, a wave hit platform and notch at 12.5 metres O.D. at Swallow Cliff and a 'marine notch' at approximately 16.5 metres O.D. at Weston-Super-Mare Old Pier (S.T. 308625).

The 10 foot raised beach' (3.1 metres) which is a 'wave cut platform' found between Portishead and Clevedon and is barren of marine deposits (Palmer 1931) was also re-levelled by Gilbertson (1974) at 'several sites between Culver Cliff and St Margaret's Bay' and found to be at 11±1 metres O.D. with an altitudinal range of over 3 metres.

Finally, the erosional level at Brean correlated with the '50 foot raised beach' by ApSimon *et al* (1961) is actually recorded by them as ranging between +40 and +47 feet O.D. (12.3 to 14.5 metres).

It is clear that the heights of these so-called marine erosional platform are fairly randomly distributed between 10 and 30 metres O.D. (Figure 4.1). Re-examination of these sites has shown that it is virtually impossible to determine whether many of these platforms are of littoral origin, the number of erosional episodes these represent or the height, duration or age of past sea-levels that might have formed them. Therefore the reconstruction of Quaternary sea-level history in the Mendip region proposed by Gilbertson (1974) (Figure 4.2) which is compiled from these features and based on correlation with the heights of Quaternary deposits in other parts of Britain and Europe, is rejected.

Raised Beach Deposits in the Mendip Region

Very few fossilised marine deposits are preserved along the coast of the Mendip region. North of the Mendips a 2.5 metre length of raised beach deposits exposed at Swallow Cliff, Middlehope (Saunders 1841) (ST.325661), and several small fragments (<3 metres) of a previously extensive raised beach are exposed along the north side of Worlebury Hill (ST.315628) (Day 1866, MacIntosh 1868, this study).

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FIGURE 4.1 : Height of 'Marine' erosion platforms in the Mendip Region.

FIGURE 4.2 : The pattern of Pleistocene sea level changes in coastal Somerset; curve shows altitudinal limit of wave activity (Gilbertson 1974).

South of the Mendips some extensive spreads of marine sands and clays of the Burtle Beds have been described from boreholes and pits (Kidson *et al* 1979). Estuarine marine deposits have also been recorded at Walton-in-Gordano (ApSimon & Donovan 1956) and at Kenn (Gilbertson & Hawkins 1977).

Swallows Cliff, Middlehope.

The Swallows Cliff raised beach was first described by Saunders (1841) and Ravis (1869). It is composed of gravel and boulder sized clasts of limestone cemented by a shelly sand matrix, and lies on an erosion platform 5-6 metres above the modern shingle beach (Gilbertson & Hawkins 1979) (Figure 4.3). This deposit was assigned to the '10 foot' raised beach stage (Palmer 1931) and assigned a mid-Devensian age (Apsimon *et al* 1961, Donovan 1962). The C^{14} dates on shells of and 33240 $^{+760}_{-700}$ years bp (NCP126A) and 38990$^{+1690}_{-1390}$ years bp (NPC 126B) (Callow & Hassell 1969) gave support to the idea of a last glacial high sea stand. However, these dates have been considered unreliable (Kidson 1970) and an 'Ipswichian' age has been assigned to the deposit on the basis of its height and the presence of a temperate molluscan fauna, consistent with interglacial conditions (Mitchel *et al* 1973, Gilbertson & Hawkins 1977).

The Worlebury Hill Raised Beach

Several fragments of what was probably once a continuous raised beach deposit can be found along the north side of Worlebury Hill beneath the Kewstoke Road. Two exposures of this raised beach have been examined, the first at Spring Cove (ST310627) which was first described by Day (1866) and MacIntosh (1868); the second, 0.5 km farther along the coast (ST318628) which has never previously been recorded (Figure 4.4). The stratigraphy of these two sections is

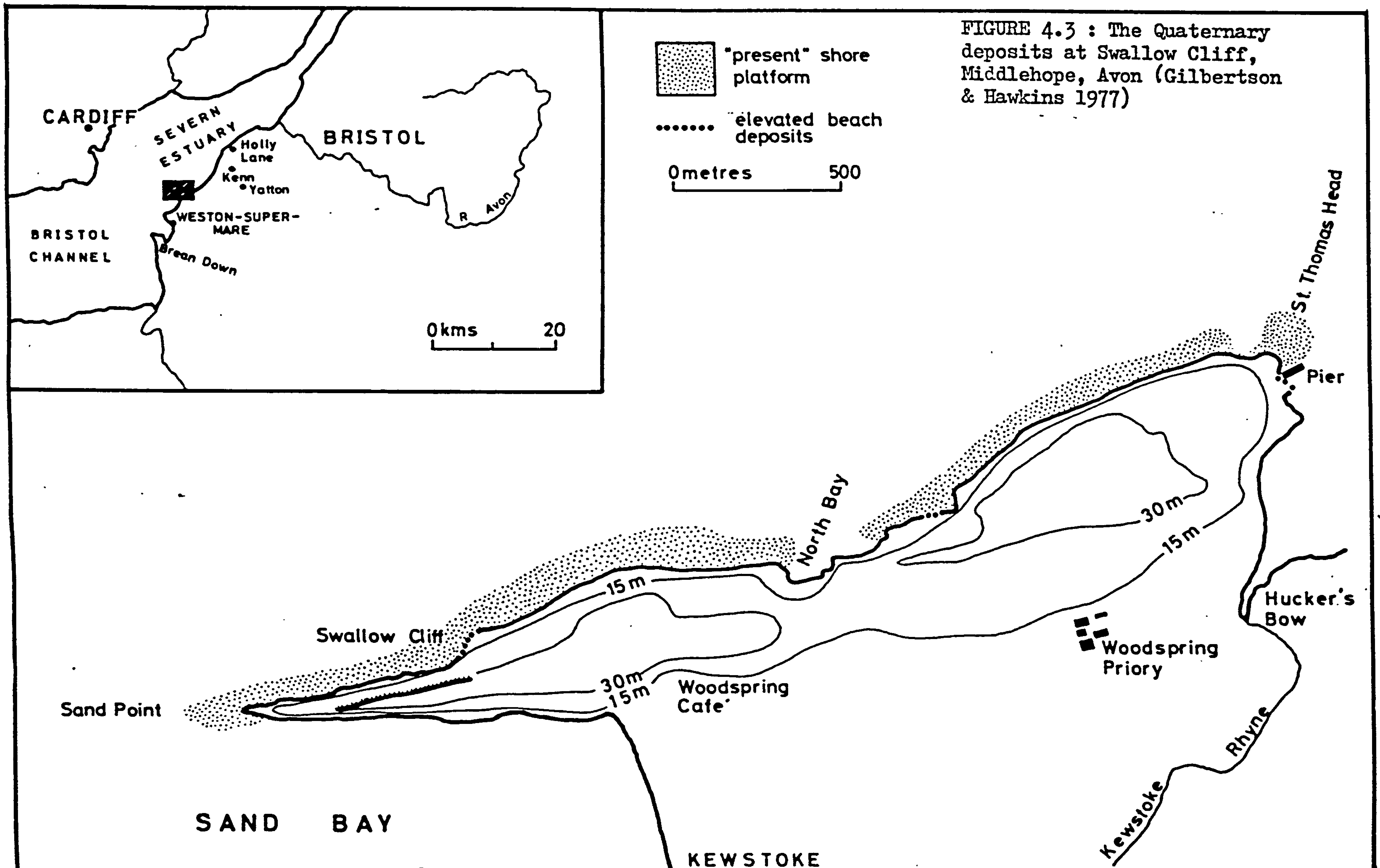


FIGURE 4.3 : The Quaternary deposits at Swallow Cliff, Middlehope, Avon (Gilbertson & Hawkins 1977)

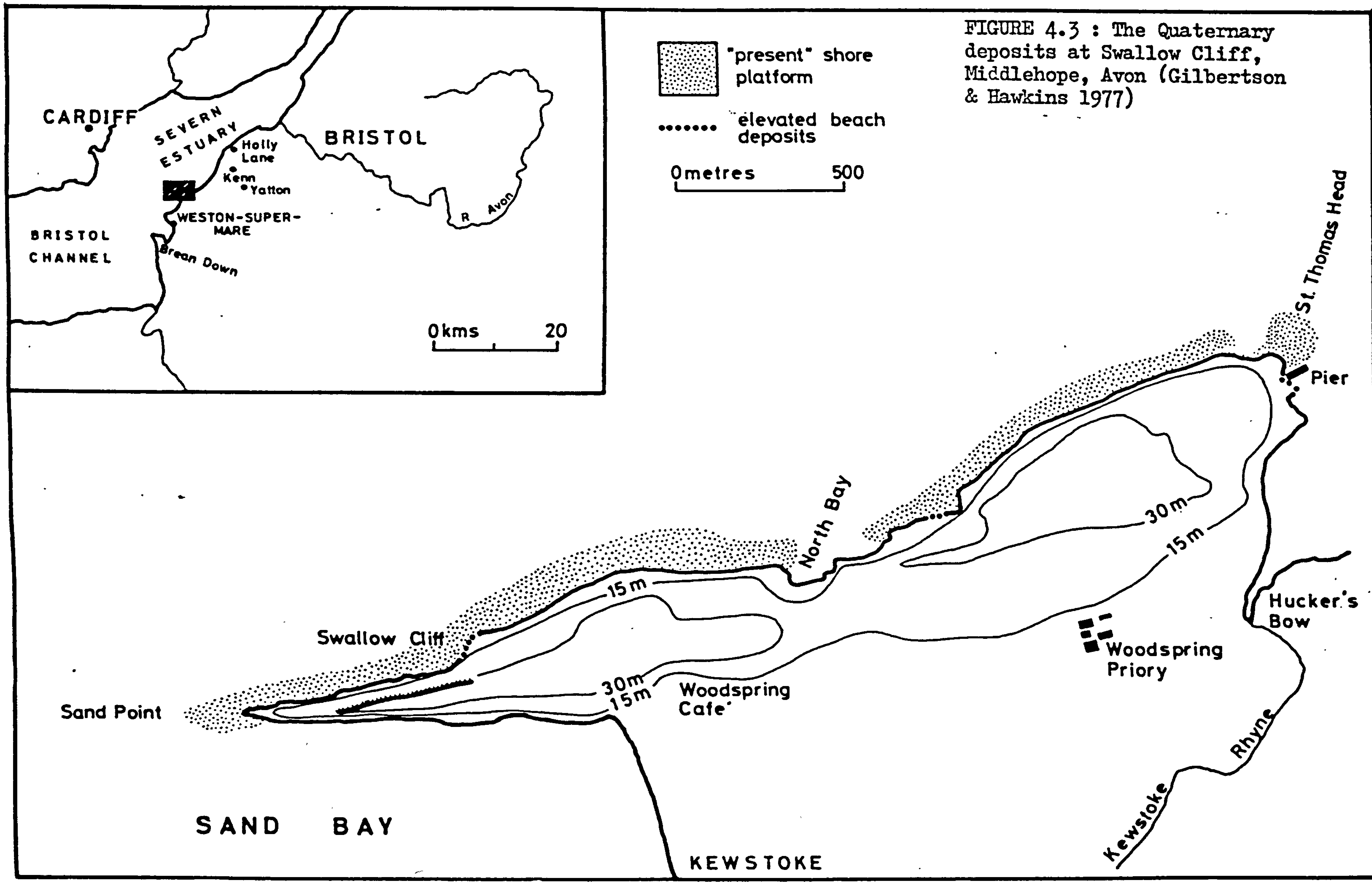


FIGURE 4.3 : The Quaternary deposits at Swallow Cliff, Middlehope, Avon (Gilbertson & Hawkins 1977)

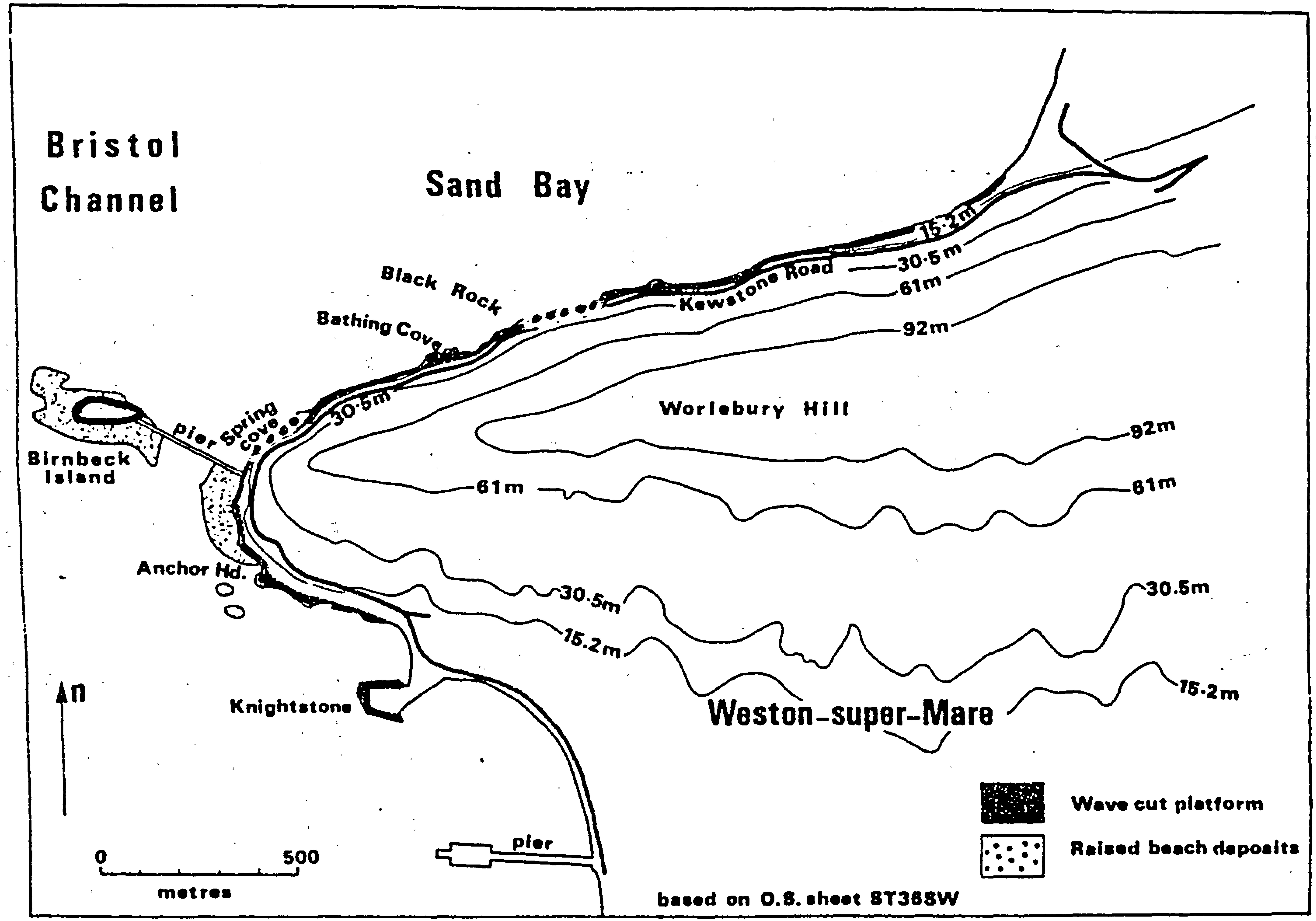


FIGURE 4.4 : Location of the Worlebury hill raised beach deposits (adapted from Gilbertson 1974).

shown in Table 4.1. As it is only possible to reach both these sections by abseiling, the accuracy of the measurements is limited to ±0.1m.

It is possible to trace these deposits along the coast where they are overlain by a complex sequence of solifluction and debris flow deposits, interstratified by wind blown sand. The two sections undoubtedly belong to the same beach deposits, although there are slight differences in stratigraphy (Table 4.1). The beach clasts are typically well rounded and similar to those from the modern shingle beach. The sand from the beach and sand rock deposits has been examined by Scanning Electron Microscopy using the method of Gordon (1983, 1986). The most prominent microtextures were impact V's, rounded and subrounded outlines, breakage blocks, conchoidal fractures, and grooves and scratches which are all consistent with a littoral depositional environment (Krinsley & Doornkamp 1973; Baker 1976; Higgs 1979). The density and size of impact V's on the sandrock grains from both deposits were similar. This probably indicates that the energy levels of their depositional environments were similar (Margolis & Kennet 1971). The sandrock material showed chemical solution and precipitation features indicating a degree of diagenesis associated with cementation. It must be stressed that qualitative microtexture analysis is not ideal for determining depositional environments (Bull 1981), particularly since many littoral textures are common to some fluvial and even some glacial environments (Setlow & Karpovich 1972; Manker & Ponder 1978). However, the stratigraphic position of these deposits (eg on top of a cliff, half way up a hill by the sea) would preclude these modes of deposition. Therefore the expense of a quantitative microtexture analysis was not warranted. Ripples preserved in the sandrock at the gully section had a crest to crest distance between 4.5 to 7cm with a mean distance of 5cm. Their height varied from 0.9 - 1.5cm with a mean of 1cm. At Birnbeck Cove the crest to crest distance ranged between 4 to 6cm with a mean of 5cm. The height was difficult to measure because of the degree of weathering but was

TABLE 4.1 : STRATIGRAPHY OF THE WORLEBURY HILL RAISED BEACH SECTIONS

Birnbeck Cove		Thickness
Obscured		3m
Head	= Matrix rich breccia composed of angular carboniferous, limestone clasts with 'A' axis up to 30cm. The deposit is class supported with a silty clay matrix. The 'A' axis of the clasts are orientated predominantly away from Worlebury Hill.	1.75m
Red Sand	= Impersistent red siliceous sand layer with limited local calcite cementation.	0.3m
Sandrock	= Siliceous sand heavily cemented by calcite. Marked cross and ripple laminated beds are evident although ripples are too heavily weathered to allow accurate measurements.	0.1m
Clay	= Red unbedded clay. Deposit is discontinuous but where present the clay/sandrock interface is very sharp (> 1cm).	0.25
Beach	= Well rounded carboniferous limestone clasts with 'A' axis up to 25cm. Deposit is clast supported with a sandy matrix. At the west end of the section the overlying deposits pinch out and the beach widens to grade into the overlying 'head'.	1m
Bedrock	= Carboniferous limestone with a platform on which the deposits lie.	5m to modern shingle beach
Gulley Section		
Upper section	made ground beneath road	0.6m
Clay	= unbedded red clay layer	1.0m
Upper Head	= Matrix rich clast supported breccia with angular carboniferous limestone clasts with 'A' axis up to 20cm. Silty clay matrix.	1.5m
Obscured		2.6m
Middle Head	= Matrix rich clast supported breccia similar to 'upper head' except locally cemented. This is possibly the same deposit as the upper head but it is not currently possible to trace a connection.	0.4m seen
Sandrock	= Siliceous sand heavily cemented by dense calcite cement with a steep 10° dip towards the sea. Cross and ripple beds are evident considerably less weathered than sandrocks at Birnbeck Cove. sand rock surface broken and recemented. Breakage was prior to the cementation of the overlying head.	0.56m
Lower Head	= Matrix rich breccia with angular limestone clasts many with some degree of edge rounding. Clast supported with a silty matrix.	0.9m
Beach	= Well rounded carboniferous limestone clasts in a sandy silt matrix.	0.15m
Bedrock	= Carboniferous limestone with prominent platform on which deposits rest. 1.6 of platform exposed.	8m to modern beach

approximately 1cm. The identical mean values of ripple amplitude and frequency in both sections support the qualitative interpretation of the microtexture analyses, that the sandrock depositional environments had similar energies.

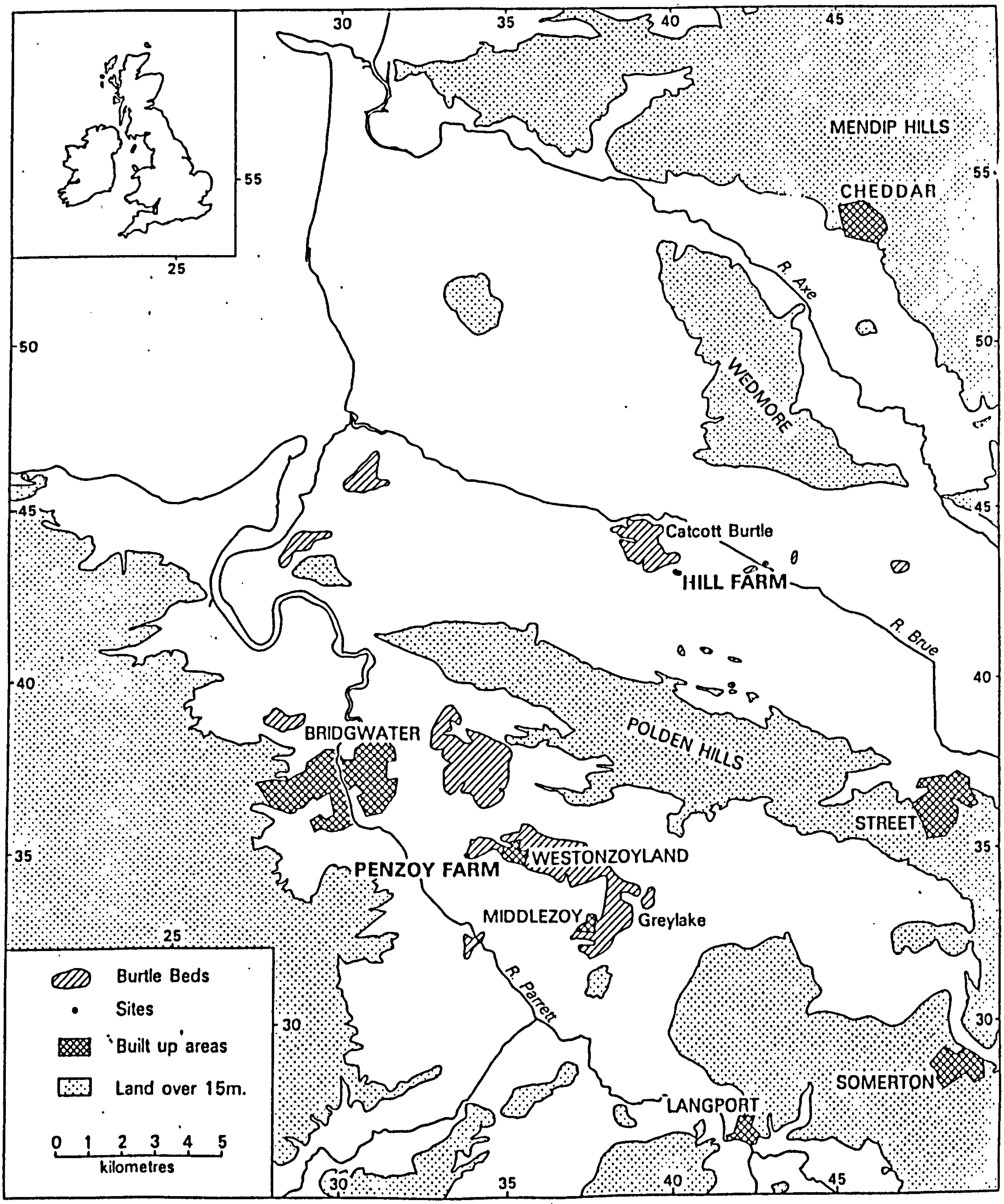
The Burtle Beds

South of the Mendips no raised beach deposits are known. However, a complex series of predominantly sand, silt and clay deposits, collectively known as the Burtle Beds, are found at several sites (Figure 4.5) (Kidson *et al* 1981). These deposits are recorded mainly from boreholes and pits and appear to be predominantly estuarine, although there has been much debate over their origin. Early work was summarised by Bulleid & Jackson (1937, 1941) who proposed a marine origin. However, fluvio-glacial deposition was proposed by Kellaway (1971) and by Hawkins & Kellaway (1973) but the presence of estuarine and near-shore marine faunas would seem to preclude this suggestion (Kidson & Haynes 1972; Kidson *et al* 1974, 1978). However, freshwater and terrestrial interglacial molluscan faunas are known from several sites (Gilbertson 1979), indicating that despite the work of Kidson and his co-workers, the complex stratigraphy of the Burtle Beds is still relatively poorly understood, particularly considering the amount of Holocene reworking that some of these deposits have undergone (Kidson *et al* 1981). Radiocarbon dates on marine shells from the Burtle Beds from heights between +8.2 and -10.7m O.D. have yielded dates of 36200 $^{+3600}_{-1800}$, 32750±1600, 29000±1000 and 33200 $^{+2300}_{-1800}$ years bp (Kidson 1970). These dates have been rejected and an Ipswichian age assigned to the Burtle Beds on the basis of their faunas (Kidson *et al* 1978; Hunt & Clark 1983).

Amino Acid Geochronology

The advent of amino acid geochronology has led to several re-interpretations and attempted inter-regional comparisons of marine

FIGURE 4.5 : Location of Burtle Bed deposits
(Kidson et al 1981)



deposits from the Mendip region. Reported values of D-alloisolucene and L-isoleucine ratios from Mendip region sites are shown in *Table 4.2.*

There are a number of problems associated with correlating and assigning ages to Mendip region deposits on the basis of these results. Firstly, the ratio obtained by Andrews *et al* (1979), and Davies (1983) on shells from Swallow Cliff differ significantly, and so do the ages and inter-regional correlations attributed to this site. Inter-laboratory differences are clearly significant: Wehmiller (1984) has shown that variations of 25% are common between some laboratories; secondly, the validity of the Burtle Beds results of *Andrews et al* (1979) has been questioned by Wehmiller (1982). Conflicting age determinations and correlations were obtained when the data from different species were compared. Finally, changes in the sample preparation method means that none of the Mendip region data is directly comparable with that presented by Bowen *et al* (1985) in their major review of the raised beaches of south west Britain. However, even when new dates become available, any correlations and age determination based upon the aminostratigraphy of Bowen *et al* (1985) should be treated with caution, for the following reasons:

1) Although intraspecific variations in epimerisation rates have been studied and attempts made to correct for differences, intraspecific variations have not been given due consideration. Selander (1976), using conventional gel electrophoresis, has demonstrated that marine mollusca have a considerable number of polymorphic loci and that average heterozygosity (8.3%) is higher than in most other groups. Considering the relatively small deme sizes and low vagility of marine mollusca it would be expected that even in the absence of local selection pressures, genetic drift alone would lead to considerable protein variation between sub-populations (Hartle 1980). However, there is a considerable amount of evidence that local selection pressures have caused considerable variation between sub-populations of several different species of marine mollusca along the Welsh coast (eg Emson & Fuller-Fritsch 1976, Raffaelli & Hughes

TABLE 4.2 : REPORTED VALUES OF D-ALLOLEUCINE & L-ISOLEUCINE RATIOS FROM THE MENDIP REGION SITES

Site	D-allo:L-iso ratios	Molluscan species	No. of shells	No. of runs	Source
Swallow Cliff, Middlehope.	0,101±0,005	Patella Vulgata	4	4	Andrews et al 1979
	≈0,20	"	≈5	≈5	Davis 1983
Burtle Beds	0,119±0,009	"	3	3	Andrews et al 1979
(Grey No 2 Pit)	0,14±0,025	Macoma Baltica	6	6	
Kenn Church	0,198±0,02?	Macoma	3	3	Andrews et al 1984
"	0,21±0,03	Corbicula	1	2	" "
"	0,104±0,005	Patella Vulgata	1	1	" "
"	0,215±0,02?	Littorina	1	2	" "
New blind drain	0,2±0,02?	Macoma	1	1	" "
Kenn Pier	0,395±0,028	Corbicula	4	4	" "
Yew Tree Farm	0,278±0,08	Corbicula	2	5	" "
Chadbrick Gravels (Hurcott Farm)	0,18	Corbicula	1	1	Hunt et al 1984
Burtle Beds (Old Sea Bank)	0,18	Corbicula	1	1	" "
(Othery)	0,26	Corbicula	1	1	" "

1978, Elner & Raffaelli 1980, Begon & Mortimer 1981, Naylor & Begon 1981). This amount of variation would surely cause measurable intraspecific differences in D-alloleucine:L-isoleucine epimerisation rates.

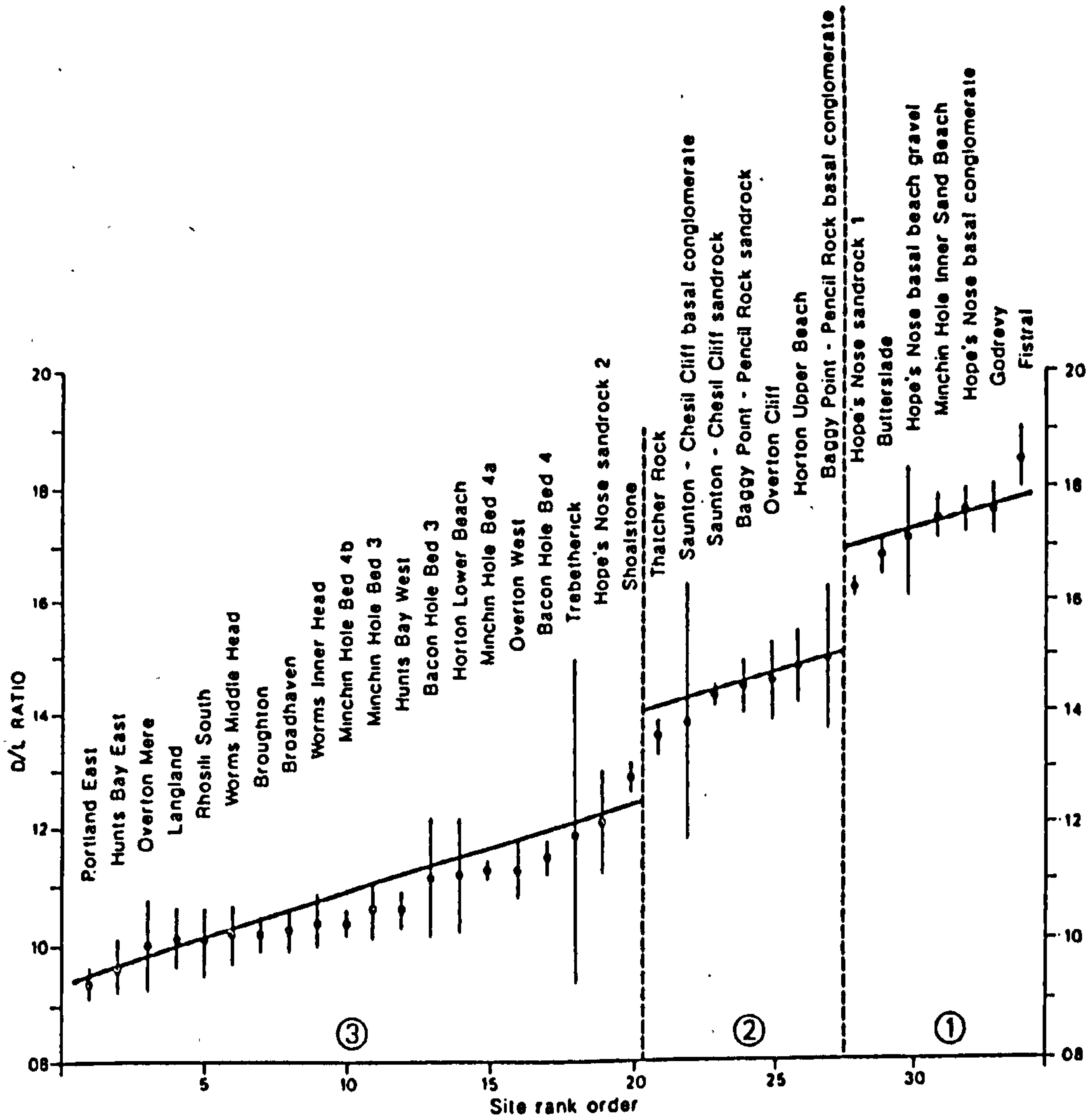
2) Bowen *et al* (1985) have identified three amino acid stages: the Pennard (3), an unnamed stage (2) and the Minchen Hole stage (1) (Figure 4.6). Although there are several possible age correlations that can be made, the most favoured is the Pennard stage with stage 5e, the unnamed stage with 7a, and the Minchen Hole stage with 7c of the deep sea oxygen isotope record (Bowen *pers comm.*). It seems somewhat problematic that stage 7 can be subdivided, but not stage 5, considering that epimerisation rates decrease with age. The 'glaciation' associated with stage 7b (c. 230000 years BP) is known to have been intense, but short, with a duration of similar length to stage 5d or 5b (Shackleton & Opdyke 1973; Ruddiman & MacIntyre 1982; Andrews 1983).

3) The partitioning of the amino groups of Bowen *et al* (1985) is based upon a realistic geological interpretation of the results of the non hierarchical clustering method of Edwards & Cavalli-Sforza (1965). However, Blashfield (1977) and Milligan (1980) have shown that group recovery achieved by non-hierarchical classification methods are highly susceptible to the initial starting position used. Furthermore, although good recovery can be achieved if the starting seed were obtained from a robust hierarchical clustering algorithm, such as Ward's method, the results are generally worse than initial partition provided by Ward's method (Scheibler & Schneider 1985). Since Bowen *et al* (1985) made no attempt to statistically verify these clusters, the validity of their groupings is open to question.

Eustatic Sea Levels and Inter-regional Correlation

The premise behind the study of marine erosional platforms and their inter-regional correlation on the basis of altitude is that it is

FIGURE 4.6 : Best estimate of amino acid stages for UK marine mollusca. 1 = Minchin Hole stage, 2 = unnamed stage, 3 = Pennard stage. (Bowen et al 1985.)



D/L Stages and characteristic D/L ratios for the different species and the standardised (to *Patella vulgata*) D/L ratios

D/L Stage	Stratotype	Mean D/L ratios
Pennard*	Minchin Hole Cave	*Pv*(Standard) 0.105 ± 0.016 (196)(204) *Pv* 0.105 ± 0.015 (79)(81) *Llra* 0.107 ± 0.016 (52)(54) *Llrs* 0.110 ± 0.013 (37)(39) *Lsax* 0.102 ± 0.007 (14)(14) *Litt. sp.* 0.108 ± 0.014 (4)(4) *Nl* 0.115 ± 0.016 (8)(10)
unnamed	undesignated	*Pv*(Standard) 0.135 ± 0.014 (42)(53) *Pv* 0.133 ± 0.015 (13)(14) *Llra* 0.147 ± 0.018 (9)(11) *Llrs* 0.135 ± 0.013 (9)(13) *Lsax* 0.134 ± 0.008 (6)(8) *Litt. sp.* 0.135 ± 0.010 (2)(2) *Nl* 0.141 ± 0.007 (3)(5)
Minchin Hole	Minchine Hole Cave	*Pv*(Standard) 0.175 ± 0.014 (42)(52) *Pv* 0.178 ± 0.014 (27)(31) *Llra* 0.176 ± 0.017 (3)(6) *Llrs* 0.177 ± 0.015 (4)(4) *Litt. sp.* 0.178 ± 0.006 (4)(4) *Nl* 0.183 ± 0.016 (6)(9)

possible to reconstruct eustatic sea level curves, ie that although tectonic and isostatic adjustments would produce different relative sea level curves in less stable regions, if allowance could be made for crustal movements, these areas, together with the stable regions, would conform to a common eustatic curve of sea level change (for example Sheppard 1960, 1967; Fairbridge 1961). Studies during the 1970s demonstrated that the large differences in sea level curves between sites around the world could not be resolved by eustatic methods (Bloom 1977; Hopley 1978).

The most important factors in determining these differences was recognised as glacio-isostacy and hydro-isostacy (Bloom 1967; Walcott 1972; Chappell 1974; Neuman *et al* 1980a). During glaciations a mass transfer will occur between the land and the sea as water is locked up globally as glacial ice. This causes increased loading upon the land and therefore depression, and decreased loading on the sea floor, which will rise. Therefore, sea level changes will relate to the distance the coast line is from deep water and glacial ice sheets.

Other associated problems in determining sea level changes are the 'dynamic topography' of the ocean surface which varies by several metres in height (Lisitzin 1965; Kidson & Heyworth 1979) and Geodial eustasy. Mörner (1976) has shown that sea levels respond to horizontal and vertical changes in the shape of the Geoid (eg westward drift, horizontal drift and gravity strength), and that there are bumps and depressions in the sea level relative to the centre of the earth (the equipotential surface of the Geoid) of as much as 180 metres. This figure is of a similar magnitude to the size of sea level changes that are thought to have occurred during the Quaternary (Jongsma 1970; Veeh & Veevers 1970; Shackleton & Matthews 1977). Considering these points, the concept that Eustatic sea level curves can be constructed which are representative of 'world wide change in sea level' can no longer be regarded as valid (Kidson 1982), each region will record a unique series of sea level changes. Studies of recent sea level changes support this contention as they show that during the twentieth century sea levels have risen at different rates over most of the globe, but that sea levels have fallen in the western Pacific (Barnett 1983). Detailed analyses of 3000 radiocarbon dated sea land indicators over the last 12000 years BP has demonstrated that the 'Holocene Geoid has apparently suffered chronic instability' (Neuman *et al* 1980a, 1980b) (Figure 4.7).

Despite these facts the idea that shorelines and erosional surfaces can be correlated on the basis of altimetric data has died hard, particularly in the regions of earlier extensive 'denudation chronological correlations' (Hey 1978; Butzer 1983).
Despite the recognition that sea level curves are not only relatively different but are absolutely different in different regions of the world because of the varying effects of glaciation upon earth rheology, it is possible to construct a numerical model of sea level change for any given region based upon a spherical visco elastic earth with varying layered structures if assumptions are made about visco elastic properties of the earth and icesheet histories (Farrell & Clark 1976; Clark et al 1978; Clark 1983). The exact sea level solution at position r and time t for any icesheet history is (Farrell & Clark 1976):

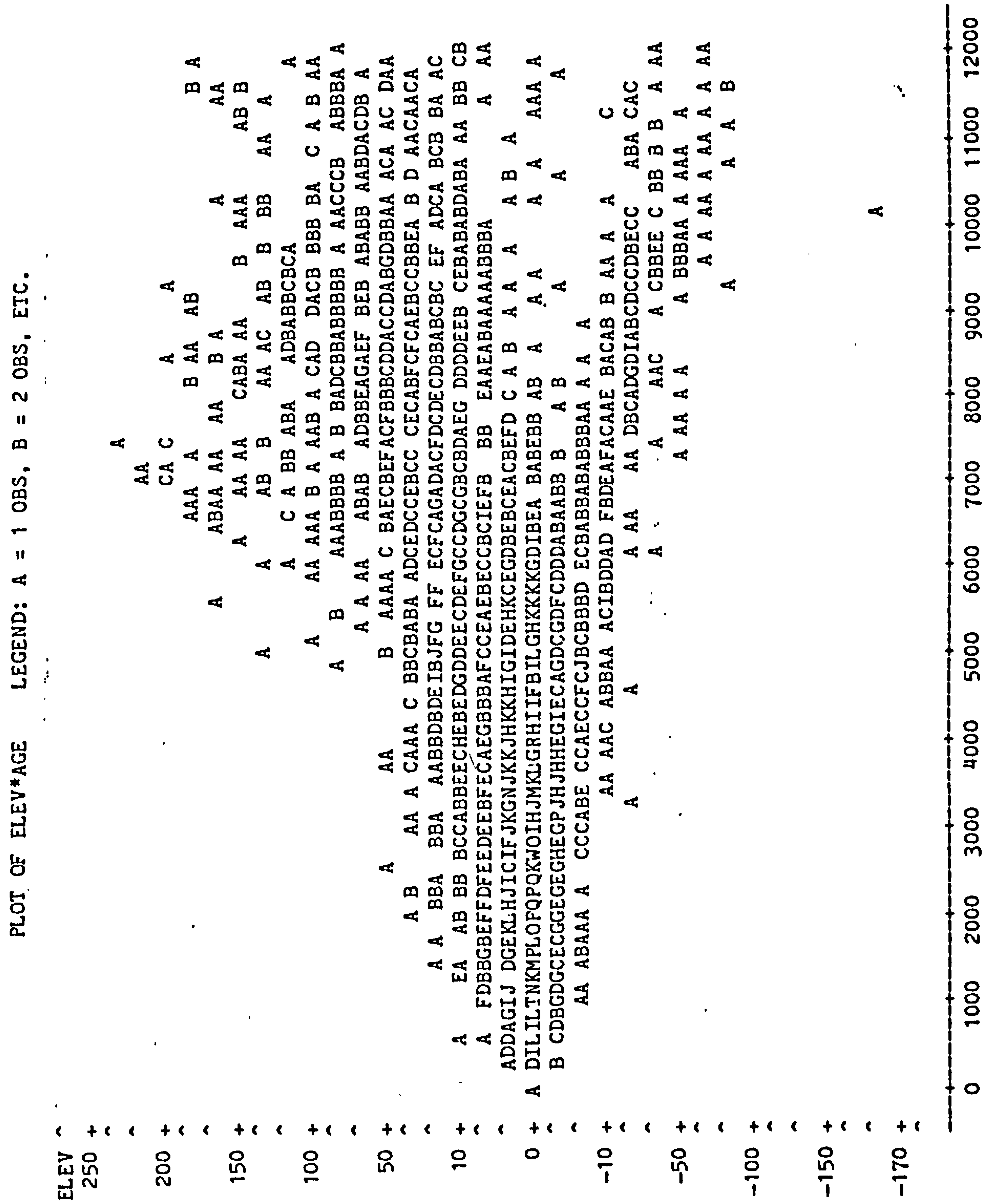
$$s(r,t) = 1/9 \int [p_w \iint_{\text{oceans}} G(r-r', t-\tau)\, s(r,\tau)\, dr' + PI \iint_{\text{ice sheets}} G(r-r', t-\tau)\, y(r'\tau)\, dr']\, d\tau - K(t)$$

where $G(r-r',t-\tau)$ is the potential response at position r and time t due to a 1 kg point load placed on the earth's surface at position r' and time τ,

- G = Green's function,
- Pw = Density of water,
- PI = Density of ice,
- K = Correction term that ensures the conservation of mass, included in K is the Eustatic sea level rise,

Clark & Lingley (1979) and Clark (1983) have shown that the results of this model fit closely to the observed sea level changes that have occurred since the end of the last glaciation in a number of regions; particularly they can account for the greater than present day sea level during the Holocene in the southern hemisphere at the same time

FIGURE 4.7 : Height of sealevel indicators (in feet) Vs radio-carbon ages. (Neuman 1980a)



as lower than present day sea levels were occurring in the northern hemisphere (Clark & Lingley 1979). A model of this nature would seem to offer the best solution for determining the sea level changes which have occurred in the Mendips during the Upper Pleistocene. In order to do this, assumptions must be made about Eustatic sea level rise which has occurred during this time.

There are *a priori* reasons for assuming that a complete record of sea level change will not have been preserved in the Mendip region. Mesolella *et al* (1969) have suggested that tectonic uplift can be regarded as the analogue of the paper drive in a strip chart recorder, while glacial Eustatic sea level oscillations drive the recording pen. If the paper does not move in this system, the pen moves back and forth over the same area producing a thick unreadable trace. If the paper moves forward slowly, large amplitude and low frequency pen motions can be distinguished while high frequency oscillations remain superimposed. Thus, the more rapid the rate of tectonic uplift, the greater the detail of sea level changes which will be preserved. This model has been shown to be valid for rapidly uplifting tropical islands fringed by coral reefs (Bloom & Yonekura 1983). It is evident that the Mendip region has only undergone limited tectonic uplift during the Quaternary; therefore it is to be expected that only records of very few sea level events will have been preserved, particularly due to the extensive weathering and erosion that occurred during glacial periods (see relevant chapters for details). Therefore, in order to estimate the Eustatic changes that have occurred, it is necessary to study regions of rapid tectonic uplift.

Although it will not be possible to determine the exact sea level changes that occurred in the Mendips from the study of these regions, the large amplitude, low frequency events caused by glacial/interglacial cycles will have affected all regions of the earth simultaneously, even if the sizes of these changes differ. It is beyond the scope of this current work to solve the model of Farrell & Clark (1976) for the Mendip region during the Quaternary.

However, a prerequisite for the solution of this model is that the number and relative size of sea level changes during the Quaternary is known. This can be better determined from the study of regions of rapid tectonic uplift (unlike the Mendips) and it will be attempted to determine the ages, number and relative sizes of large-scale sea level changes which have occurred globally, which are likely to have affected the Mendip region.

Quaternary Sea Levels : The Coral Record

Since the pioneering work of Barnes *et al* (1956), our knowledge of sea level changes in many parts of the world has been revolutionised by the uranium-series dating of corals. The dating of emerged coral reefs in tectonically unstable areas (particularly Barbados and New Guinea) have been the 'backbone of sea level studies', since the reefs provide both accurate sea level indicators and datable material (Cronin 1982). During the past 30 years over 400 uranium-series analyses of fossil corals have been published from over 30 regions of the tropics and sub-tropics (Figure 4.8). Moore (1982) has reviewed much of these data and highlighted a number of problems with the record, particularly in determining the number and ages of high sea level stages recorded and the conflicting evidence of a dated high sea level stand circa 140000 years BP with Milankovitch forcing functions. Grün & Brunnackner (1983) have attempted to resolve the problem of the number of sea level maxima by statistical analysis using the method of Hennig *et al* (1983). They identified a maximum sea level at 125000 years BP and four sea level maxima occurring between 100000-110000 years BP, 78000-86000 years BP, 56000-64000 years BP and 38000-46000 years BP. This is considerably fewer periods than are identified from the emerging terraces in New Guinea and Barbados (Bloom *et al* 1974; Chappell 1974; Chappell & Veeh 1978). As argued previously (Chapter III), Gordon & Smart (1984) have shown that the method of Hennig *et al* (1983) is statistically unsound and therefore the analysis of Grün & Brunnacker (1983) can be disregarded.

FIGURE 4.8 : Location of world coral reef uranium-series dated sites.

More recently Kaufman (1986) has attempted a limited statistical analysis of the data in order to resolve the problem of the high sea level occurring about 140000 years BP at variance with Milankovitch forcing functions. Kaufman's (1986) analysis was much more rigorous than that of Grün & Brunnacker (1983). Unlike them, he rejected unreliable uranium-series analyses on coral, which would distort the data set, using the following criteria:

1) All samples must contain less than 5% calcite, since recrystallisation from aragonite to calcite can lead to migration of uranium.

2) All samples must have a measured $^{234}U/^{238}U$ ratio rather than an assumed value equal to 1.15 (that of present day sea water).

3) All data from tectonically active coasts, eg only *in situ* samples from terraces below 11 metres in height.

Kaufman (1986) compared the remaining 108 dates with the results of a computer simulation of a normal distribution mixing model with two closely spaced peaks. He concluded that if two high sea level stands occurred during the last interglacial period (LIP), then they could not be separated temporally by more than 7500 years, and that the first could have occurred no earlier than 129000 years BP and the second no later than 122000 years BP ago. There was no evidence for a high sea stand 140000 years ago.

The work of Kaufman (1986) can be criticised on two points:

1) As was discussed in the last section, the idea of 'stable' coastlines during the Quaternary is no longer tenable. Therefore the exclusion of data from coral terraces above 11m OD is erroneous and may possibly have biased the data.

2) Only the mean values of the $^{230}Th/^{234}U$ ratios are used in the analysis and the errors in measurement are then estimated. Since

the counting uncertainties associated with the $^{230}Th/^{234}U$ ratios are known and vary from analysis to analysis, the exclusion of these data calls the analysis of Kaufman (1986) into serious question.

Distributed Error Weighted Frequency Curve Analysis of World Coral Data

Considering the problems associated with previous attempts at statistical analysis of the uranium-series dated coral reefs, a re-analysis using a modified distributed error weighted frequency curve technique of Gordon & Smart (1984) was undertaken. 244 U-series analyses were available of which 184 were considered reliable (Table 4.3), using modified criteria to those proposed by Kaufman (1986):

1) Age determinations were considered reliable if less than 5% calcite was present (eg Szabo *et al* 1978, Bloom *et al* 1979) or if concordant Protactinium dates were quoted (eg James *et al* 1971).

2) Age determinations were considered reliable when specific values for % calcite were not quoted if authors stated that recrystallisation had been checked for and $^{230}Th/^{232}Th$ ratios were greater than 20.

3) Analyses were considered unreliable if there was evidence of ^{230}Th contamination, even if calcite percentages were negligible (eg Cronin *et al* 1981).

The geographical distribution of the data is shown in Table 4.3. Most of the analyses come from the western Pacific areas and the Caribbean, with a lesser number from the central and eastern Pacific, Atlantic and Indian oceans.

It must be stressed that this study is of a preliminary nature only; a comparison of Table 4.3 and Figure 4.8 shows that data are available from several more sites than used in this study. However geographical coverage and number of dates available for analysis is

TABLE 4.3 : WORLD CORAL REEF URANIUM-SERIES ANALYSIS

Region	Reliable Analysis	Unreliable Analysis	No.of Sites
Barbados	6	17	9
Bahamas	15	15	14
Bermuda	31	1	>15
Jamaica	5	0	1
Yucatan, Mexico,	5	2	2
Antilles	8	3	2
South East Coastal Plain, USA,	5	6	11
California, USA,	2	1	2
Florida, USA,	5	16	4
Hawaii, USA,	4	0	2
Cook Islands	2	0	1
Tuamotu Island	5	0	2
Marshall Islands	7	0	4
New Hebrides	8	0	4
Timor	19	3	5
New Guinea	25	0	>11
Australia	15	0	4
Seychelles	2	0	1
Mauritius	1	0	1
Aldabra Atoll	8	0	1
Red Sea Coast, Egypt,	4	0	1
	182	62	>107

probably sufficient to indicate the major trends. Potential problems arising from incomplete coverage will be discussed below.

The distributed error weighted frequency curve of the uranium-series world coral data is shown in Figure 4.9. Apart from the Holocene peak, four other peaks representing high sea level stands can be resolved centred at 124000 years BP, 80500 years BP, 63500 years BP and 43000 years BP. This is considerably fewer than the number of high sea level stands recorded in tectonically rapid uplifting regions or by the statistical analysis of Grün & Brunnacker (1983). However, the peak centred on 124000 years BP is extremely large and broad, the reasons for which may be two-fold:

1) The record is distorted by inaccurate uranium-series analysis.
2) The record is distorted by imprecise uranium-series analysis causing the merging of several distinct peaks into one broad composite one.

It is possible to test the distorting effects of the inclusion of potentially inaccurate dates. As discussed previously, uranium migration can occur during recrystallisation which will cause inaccurate analysis. Figure 4.10 shows the effects of progressively excluding all uranium-series analyses on coral with greater than 5%, 3% and 1% calcite content. The largest peak remains centred around 124000 years BP with a small shift that is probably due to sampling error effects as sample size decreases. However, the shoulder associated with this peak shifts its position from being centred at 78000 years BP to 91000 years BP. The 3% calcite curve shows some evidence of two distinct shoulders being present, with the 91000 year shoulder becoming visible as the size of the 124000 years BP peak decreases. The discrepancy of the 80000 years BP shoulder in the 1% calcium curve indicates that the age determinants associated with the 91000 years BP shoulder and 124000 years BP peaks are more accurate than those associated with the 78000 years BP shoulder.
The effects of imprecise age determinations are shown in Figure 4.11 which displays the effects of the progressive removal of ages with

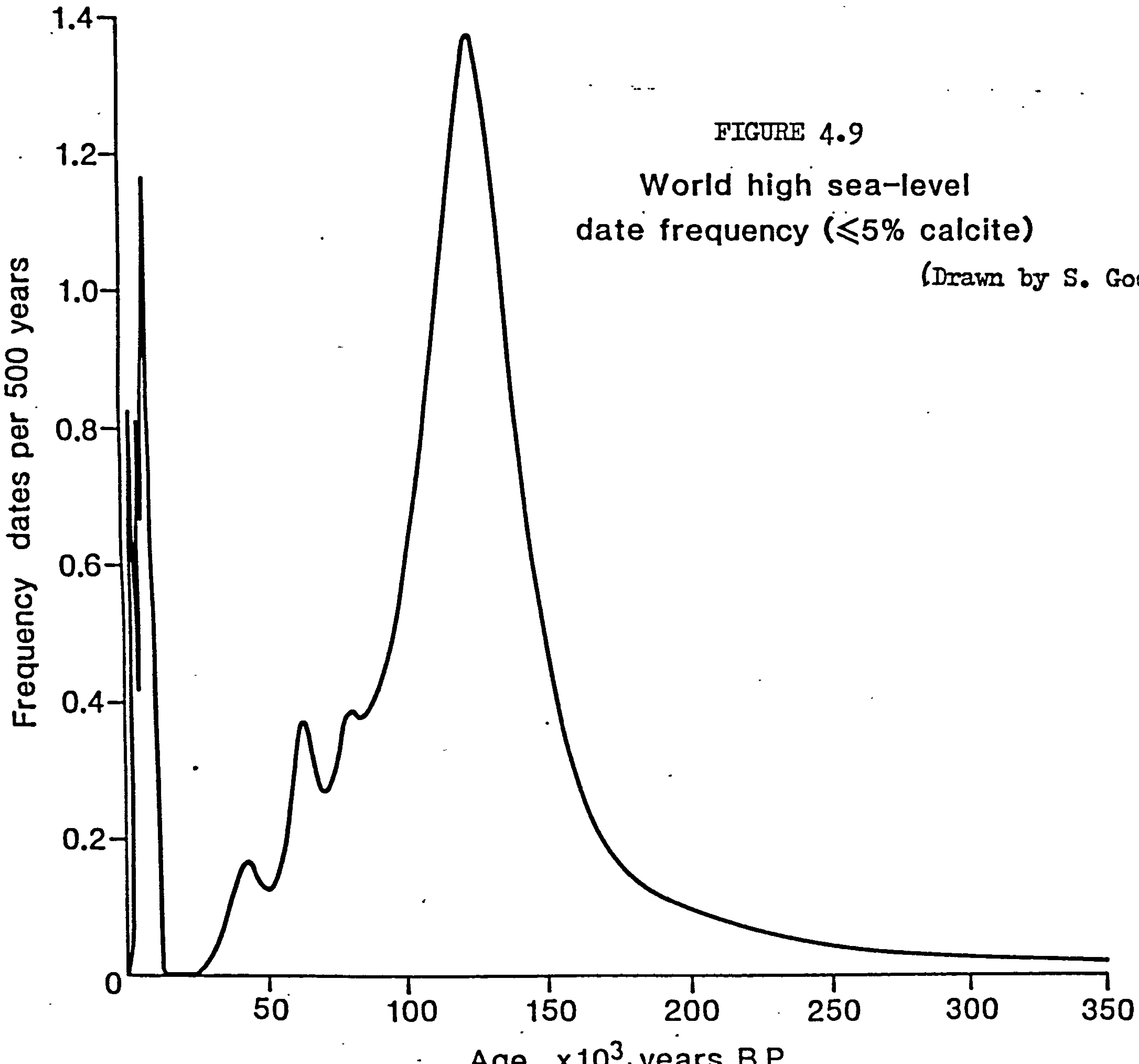


FIGURE 4.9

World high sea-level date frequency (≤5% calcite)

(Drawn by S. Godden.)

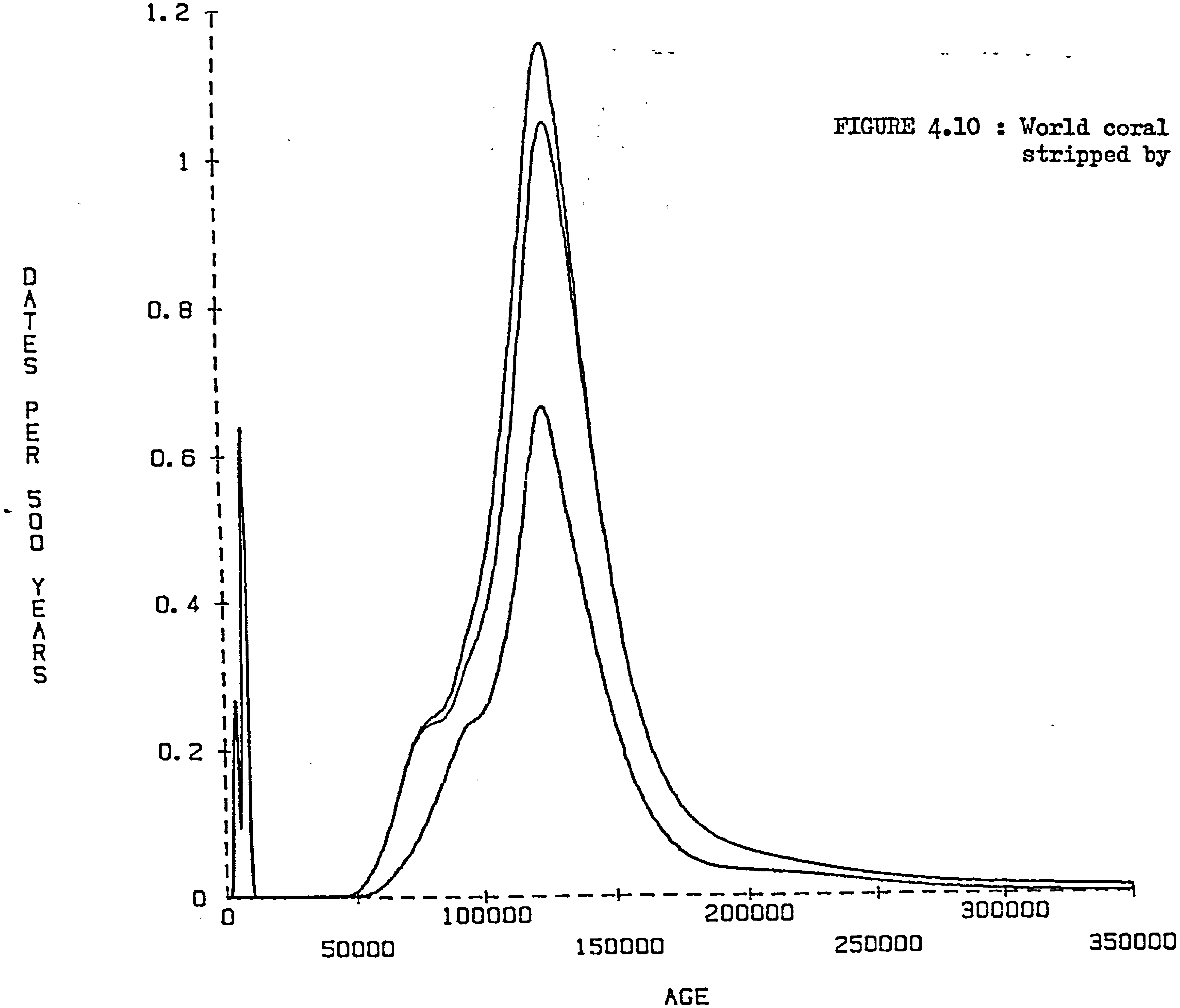


FIGURE 4.10 : World coral reef age frequency stripped by % error.

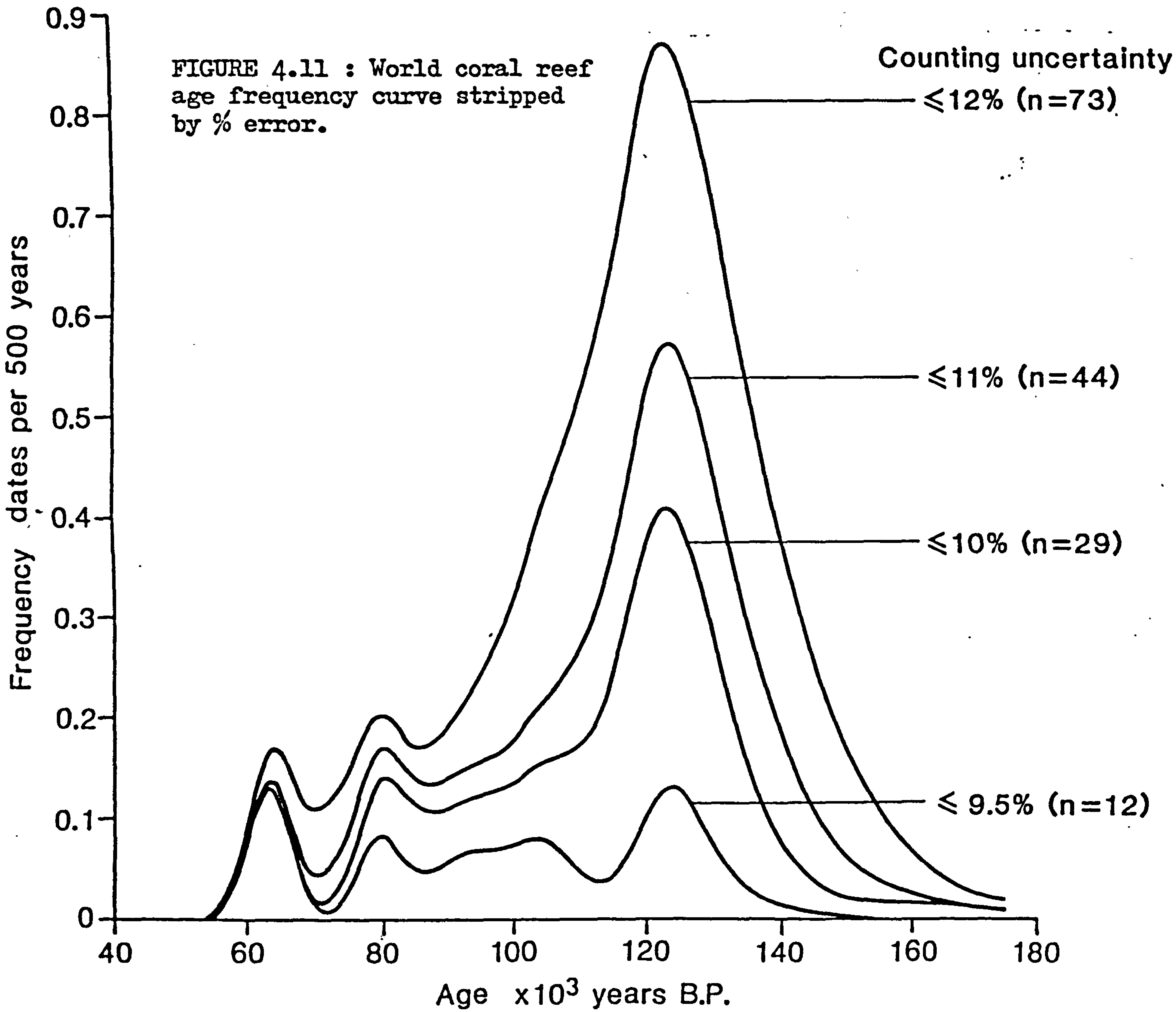


FIGURE 4.11 : World coral reef age frequency curve stripped by % error.

precisions less than 12%, 11%, 10% and 9.5% of the mean value. The broadness of the 124000 years BP peak can clearly be seen to be due to peak interference, with three distinct peaks being resolved by the progressive stripping. By comparing the results of the progressive stripping (Figure 4.11) in conjunction with calcite stripping (Figure 4.10) and the initial results (Figure 4.9) it is possible to resolve eight peaks during the Pleistocene period and make best estimates of their central ages (Table 4.4) These peaks have been designated Sealev 1-8 (sea level 1-8) as they are considered to represent the best estimates of periods of coral reef growth associated with high sea level stands. Not all these peaks can be considered to be dated with equal reliability. Peaks Sealev 7 (173000 years BP) and Sealev 8 (210000 years BP) are represented by very few dates, while peak Sealev 1 (43000 years BP) is represented only by relatively imprecise data. Peak Sealev 6 (124000 years BP) is the most securely dated, with peaks Sealev 2 (63000 years BP) and Sealev 3 (78000 years BP) being represented either by fewer or less accurate age determinations. Peaks Sealev 4 (92000 years BP) and Sealev 5 (103500 years BP) suffer from mutual peak interference (see Chapter III). The true ages of peak Sealev 4 and Sealev 5 are probably slightly younger than the quoted age of 92000 years BP and slightly older than the quoted age of 103500 years BP. Although these qualifications should be borne in mind, these results probably represent the best estimate currently available of the number and timing of high sea level stands during the upper Pleistocene.

Table 4.5 lists the relative or Eustatic sea levels associated with the 8 Pleistocene high sea level stands from 17 regions of the world. As would be expected from the results of glacio, hydro and geoidal isostatic studies (see previous discussion) the Eustatic sea levels reconstructed from different regions vary significantly. For example, the range of Eustatic sea levels associated with peak Sealev 5 (103500 years BP) is 25 metres, which is a variation of similar magnitude to the sea level of the 'Holocene maximum' (c5000 years BP - Figure 4.7) (Neuman *et al* 1980a). Although some of this

TABLE 4.4 : BEST ESTIMATE OF PEAK CENTRE AGES FROM URANIUM-SERIES DATED CORAL REEFS OF THE WORLD

Peak Designation	Centre Position Age in Years BP
Sealev 1	43000
Sealev 2	63000
Sealev 3	78000
Sealev 4	92000
Sealev 5	103500
Sealev 6	124000
Sealev 7	173000
Sealev 8	210000

TABLE 4.5 : ESTIMATE OF EUSTATIC SEA LEVELS FOR SEA LEVEL PEAKS 1-8 (Data in brackets is present elevation)

Region	Sealev 8 210000	Sealev 7 170000	Sealev 6 124000	Sealev 5 103500	Sealev 4 92000	Sealev 3 78000	Sealev 2 63000	Sealev 1 43000	Reference
Barbados	-12m	-22m	+2 to +4m +6±2m	-12±2m -16±3m		-15±3m	-20m		Mesolella *et al* 1969, James *et al* 1971, Matthews 1973, Bender *et al* 1973, Harmon *et al* 1978b,
Bahamas		+6m	+6m	+6m					Carew & Mylorie 1986
Bermuda	+1 to 3m	-6 to -20m	+4 to +6m +2 to +6m	-15 to +5m	-15m +5 to +8m	-15 to -20m	>-3m	>-15m	Harmon *et al* 1978b,1981,1983,
New Guinea	(330m)	-20 to -30m	+6 to +8m	-14 to -15m		-13 to -20m	-28m	-38±5m	Bloom *et al* 1974, Chappell 1974, Chappell & Veeh 1978 Aharon *et al* 1980 Aharon & Chappell 1986
Atlantic Coastal Plain U.S.A.		+7±5m	+7,5±1,5m		+6,5±3,5	+7±3m			Cronin *et al* 1981
Riukia, Japan.			+6m		-15m	-20m	-20m	-40m	Konishi *et al* 1970
Jamaica			+5m		+5m				Moore & Somayajulu 1974
Hawaii			+3m	+1,5m					Veeh 1966, Ku *et al* 1974
W.Australia			+4m	+2m					Veeh 1966
Seychelles			+9m			+6m			Veeh 1966
Cook Islands				+2m	+2m				Veeh 1966
Red Sea Coast, Egypt.					+2 to +8m				Veeh & Giegengack 1970
Queensland, Australia				+2±1m					Picket *et al* 1985
Aldabra Atoll			>+8m						Thompson & Walton 1972
New Hebridies			(+100 to72m)			(+55m)	(+56 to 49m)		Neff & Veeh 1977
Enewetah Atoll, Marshall Islands			(-10 to -15m)						Szabo *et al* 1985
California, U.S.A.			(+32m)	(+17m)					Valentine & Veeh 1969, Muhs & Szabo 1982.
Range of Eustatic Sea Level Estimates;	15m	42m	7m	25m	30m	8m	8m		

variation may be due to slight differences in the timing of the sea stands between sites and the integration of variations in sea level during a single peak, it would take a considerable amount of special pleading to explain away the entire range of recorded values in this manner. Considering this it seems unlikely that it will ever be possible to reconstruct a Eustatic sea level curve with an accuracy of better than ±5 to ±10 metres (as previously discussed the concept of a Eustatic sea level curve is itself of dubious validity). Therefore, the assertions of many authors that the last interglacial sea level (c 125000 years BP) was globally at +6 metres (Harmon *et al* 1980) is unlikely to be correct (Butzer 1983). The idea that Eustatic sea levels have only once been above present day values during the upper Pleistocene (Mesolella *et al* 1969; Bloom *et al* 1974; Harmon *et al* 1978b, 1981, 1983) is also probably wrong. There is now considerable geomorphological and dating evidence of post Sealev 6 (124000 years BP) sea levels at >0mO.D. in many parts of the world (Neumann & Moore 1975; Stearns 1976; Bernat *et al* 1978; Davies 1981; Cronin 1982).

The Problem of Additional Records of High Sea Stands

Although eight periods of Pleistocene high sea level stands have been identified during the past 220000 years BP, a number of additional stages have been noted by other authors that are not recognised in this study. There are three possible reasons for this:

1) The data used have insufficient coverage to identify all the high sea level stands that occurred.

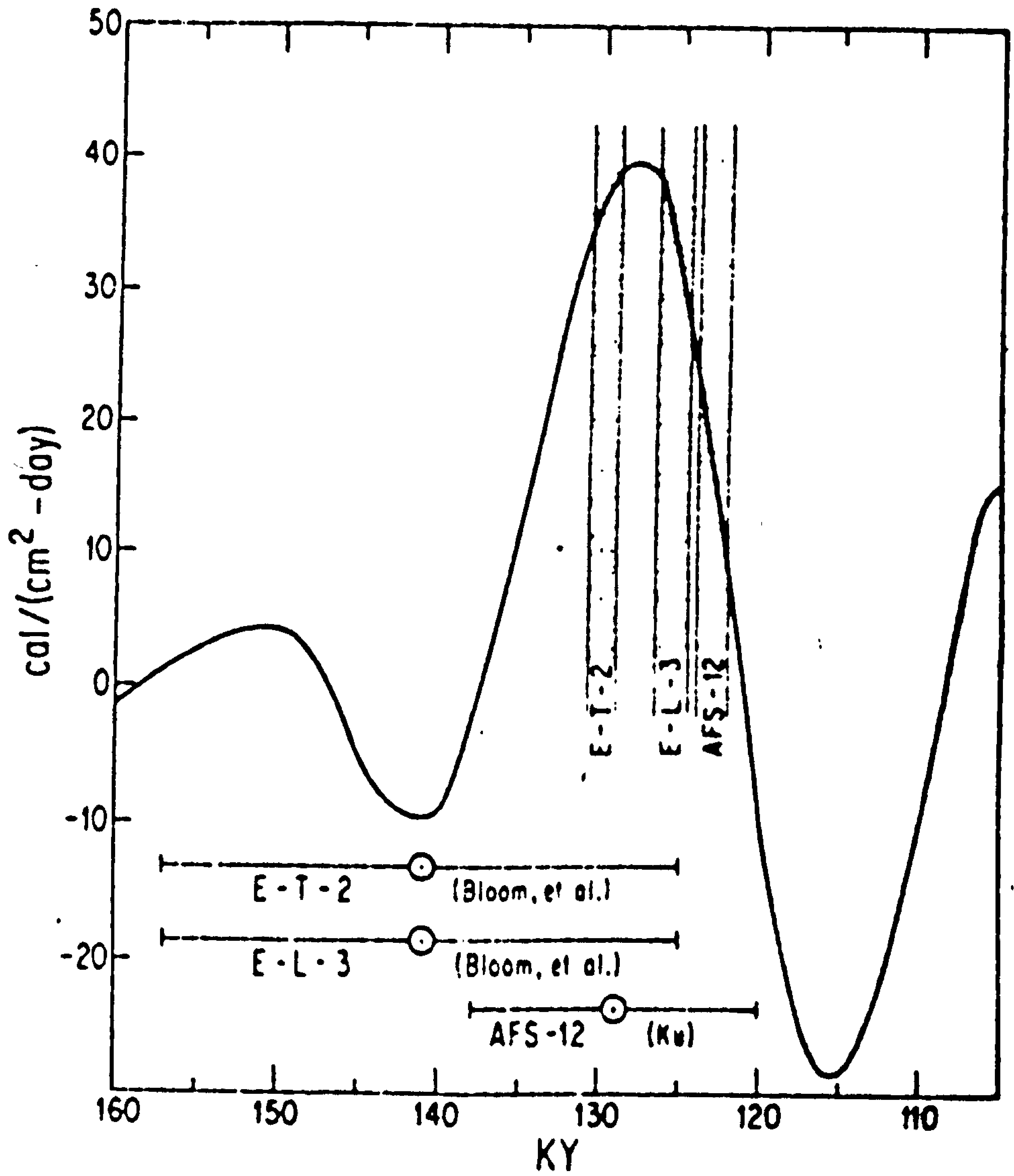
2) The resolution obtainable by the distributed error weighted frequency curve method is insufficient to resolve closely spaced high sea level stands.

3) The dating of additional stands recorded by other authors is inaccurate or imprecise.

Considerable debate has occurred over the existence of a high sea level stand around 135000 to 140000 years ago which has been recorded from sites in New Guinea, Timor and Atauro Island (Chappel & Veeh 1978; Moore 1982). This period corresponds with low solar insolation and therefore the establishment of a simultaneous high sea stand would falsify the links between Milankovitch parameters and global ice volume. A tenuous explanation based upon Antarctic ice surges has been proposed to explain this anomaly (Aharon et al 1980). However, it seems more likely that the 140000 years BP high sea stand is a statistical artifact from imprecise and/or inaccurate uranium-series analyses. Recent re-analysis of some of the key New Guinea coral samples by mass spectrometry (see Appendix 1) supports this conclusion (Figure 4.12; Edwards *et al* 1987). The original dates of 141000±16000, 141000±16000 and 129000±9000 were respectively recalculated to 125500±1300, 129900±1100 and 122700±1300 years BP. These new age determinations agree with the older values at the 2σ level but their much greater precision indicates the existence of only one high sea stand corresponding with peak sealev 6 (124000). Therefore, the interpretation of the New Guinea terrace sequence of Bloom *et al* (1979) is now in need of revision.

Terrace II in New Guinea has been dated by ^{14}C at 28900±1400 years BP (Bloom *et al* 1979) and coral terraces in Timor have been dated at 31000±2500 years BP (Chappell & Veeh 1978). A minor high sea stand may have occurred c.30000 years BP but the coverage of this preliminary study is not sufficient to detect it. Additionally, the relatively small sample size suggests that additional high sea stands may also have occurred between 350000 and 180000 years BP to those resolved in this study. There is some evidence from He/U dating of coral terraces in Barbados of high sea stands at 163000±36000, 180000±10000, 217000±6000 and 235000±34000 years BP.

FIGURE 4.12 : Average solar insolation at 65^0 North and the conventional uranium-series dates of Bloom et al (1974) compared to mass-spectrometer uranium-series ages on the same samples (Edwards et al 1987).



A more detailed future study of all the uranium-series analysis data will be useful to corroborate the existence or absence of these additional high sea stands.

Sealevel Changes and the Speleothem Record

It is possible to cross-validate the speleothem growth record and the coral terrace sealevel record by comparing them. 'Milankovitch' forcing factors have been shown to correlate with periods of speleothem growth in the UK (see Chapter III). There is also an evident linkage between 'Milankovitch' insolation and global ice-volume cycles, which control world sealevels (Ruddiman & MacIntyre 1982). Therefore, it would be expected that periods of increased speleothem growth in the UK will coincide with periods of coral reef formation during high sea stands in the subtropical and tropical regions of the world, although leads and lags will certainly occur due to the many local factors that influence both speleothem and coral growth.

A comparison of the distributed error weighted frequency curve of the precise uncontaminated data of coral reef growth and UK speleothem growth is shown in Figure 4.13. The degree of correlation is remarkable, although there are noticeable lags and leads between the two records. These may well be genuine; however, there is some evidence that the size of these lags and leads is smaller than initial examination reveals. The small sample size and the effects of peak interference distorts the two records, particularly the sea level curve. Figure 4.14 shows the ages of the central peak positions for the sealevel curve. These differ slightly from the best estimate positions of the peaks calculated by examining the accuracy as well as the precision of the uranium-series determinations (Table 4.4). A comparison of the best estimate central peak ages for the sealevel record and the UK

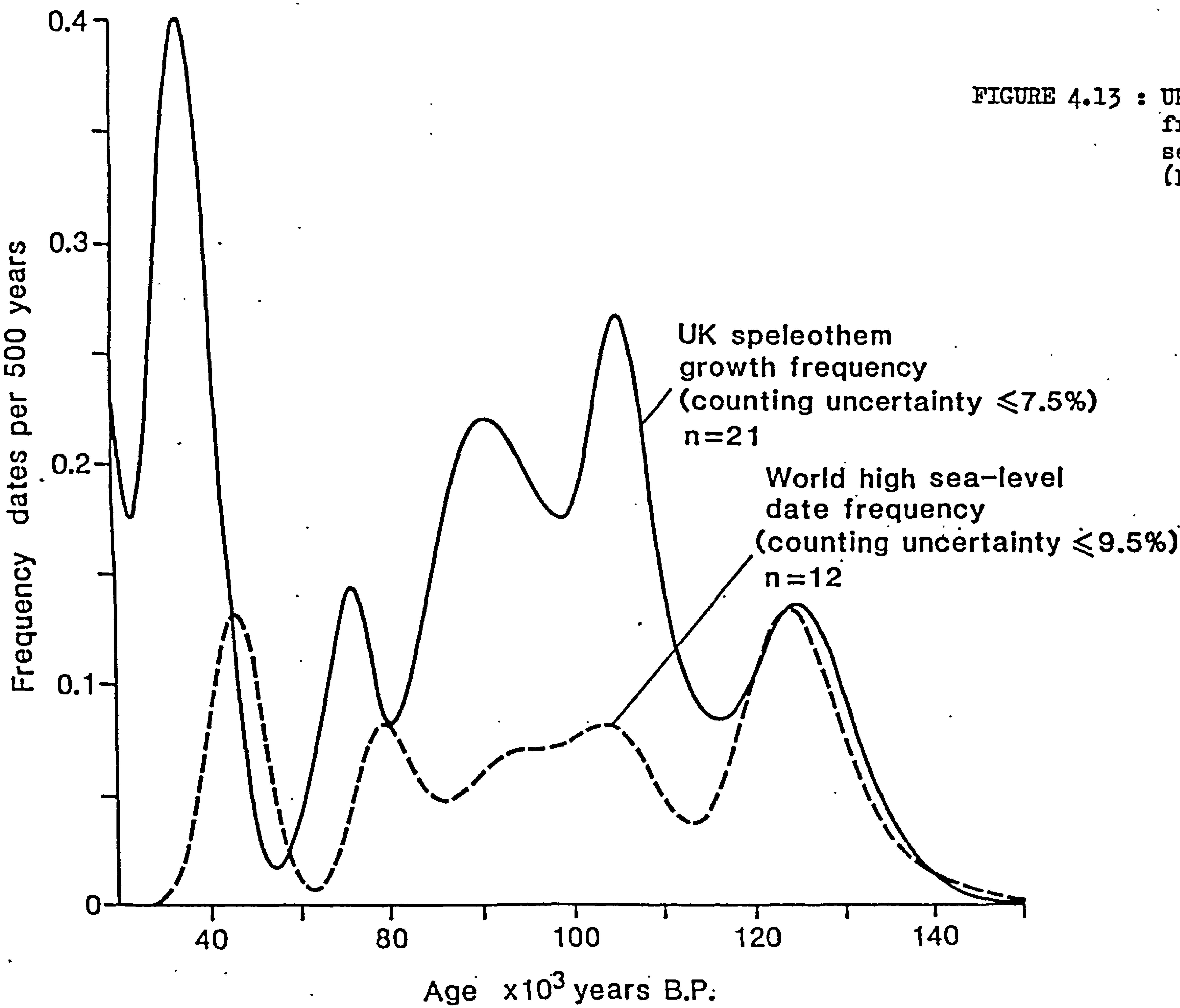


FIGURE 4.13 : UK Speleothem growth frequency Vs world high sea level date frequency. (Drawn by S. Godden.)

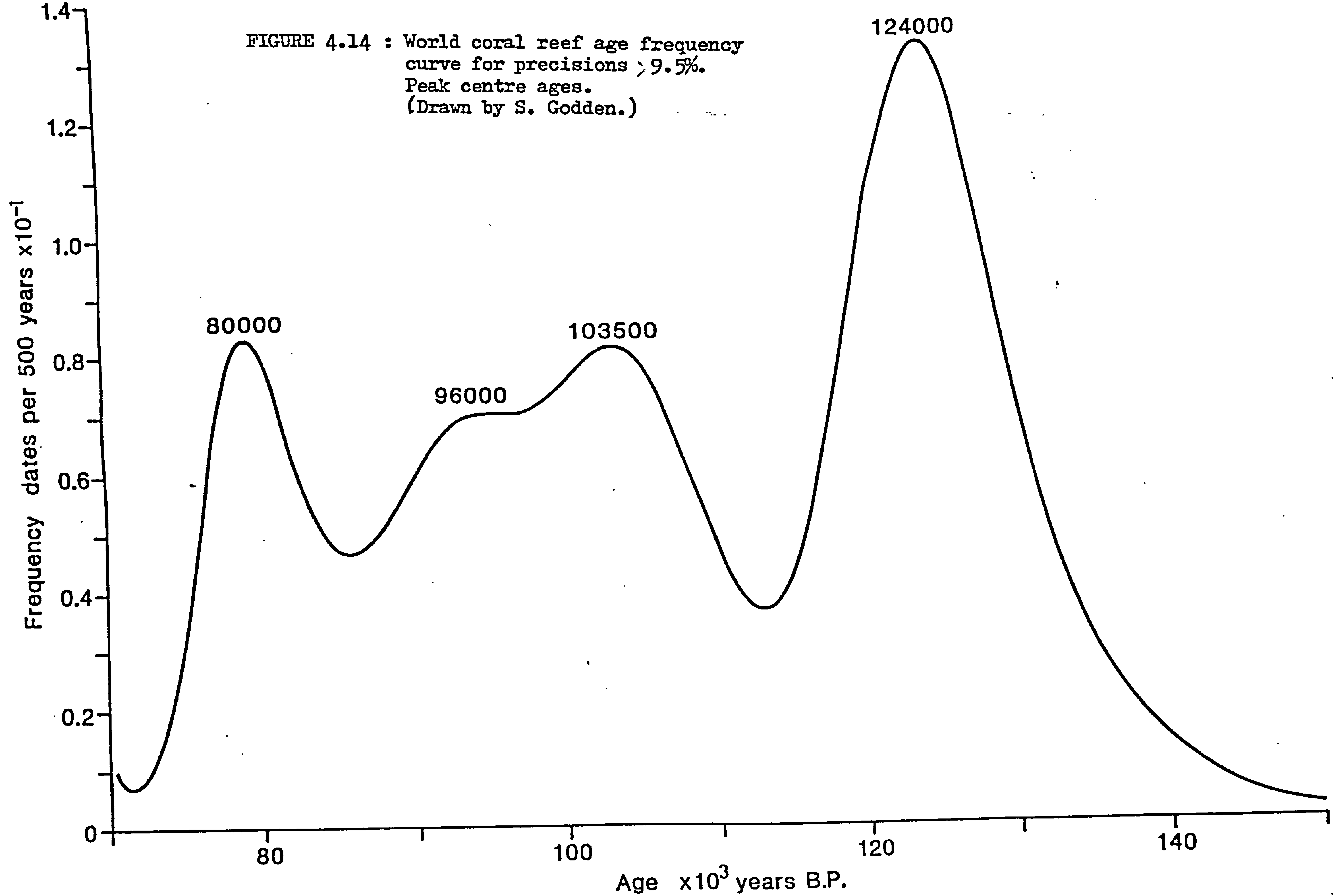


FIGURE 4.14 : World coral reef age frequency curve for precisions > 9.5%. Peak centre ages. (Drawn by S. Godden.)

speleothem growth record shows an even greater degree of correlation (Table 4.6).

However, in order to compare these results statistically, the continuous curves must be used rather than the best estimate ages. It is not possible to perform a cross-spectral analysis on the entire data set because the size of the 58000 years BP peak in the UK speleothem record causes marked non-stationarity in these data as defined by standard autocorrelation analysis (Jenkins & Watts 1968, Fishman 1969). However, the curves between 70000 and 140000 years BP (Figure 4.15) display an acceptable level of stationarity and therefore statistical comparison of this section of the data are probably valid. Cross-spectral analysis was carried out using the distributed lag model developed by Hannan (1963, 1965, 1967) as implemented in the 'Kasper' programme (supplied to me by Dr R Dunn). The distributed lag analysis is performed in the frequency domain (rather than the time domain) because of a number of statistical advantages:

"1) Unconstrained distributed lags which include both leading and lagging terms are easily estimated.

2) Dynamic responses are efficiently distinguished from autocorrelated or other error processes.

3) The estimation procedure is efficient in the presence of dependence in the errors, and the nature of this dependence need not be specified in advance." Dunn (1983,a).

The results are shown in Figure 4.16 and demonstrate that the only significant correlation is at lag 0, with some minor evidence of both positive and negative lags which probably result from noise. The t-value at lag 0 is 23 with 161 degrees of freedom, which is significant at better than the 1% level. This high degree of cross-correlation has been confirmed using standard 'time-domain' cross-spectral techniques. Examination of the phase, gain and

__TABLE 4.6 : COMPARISON OF TROPICAL & SUBTROPICAL CORAL TERRACE GROWTH PERIODS WITH FISSION TRACK AND URANIUM- SERIES DATE 'STROMBUS' RAISED BEACHES IN THE MEDITERRANEAN.__

Peak Designation	Best Estimate Centre Position Ages in Years BP	Fission Track Ages in Years BP (*mean of 6 dates)	Uranium-Series Ages in Years BP
Sealev 1	43000		
Sealev 2	63000		
Sealev 3	78000		75000
Sealev 4	92000	90000±18000	95000
			98000±6100
Sealev 5	103000		110000±5000
			115000-
Sealev 6	124000	124000±8000*	125000-
			125000±10000
Sealev 7	173000	177000±30000	
Sealev 8	210000		210000±10000

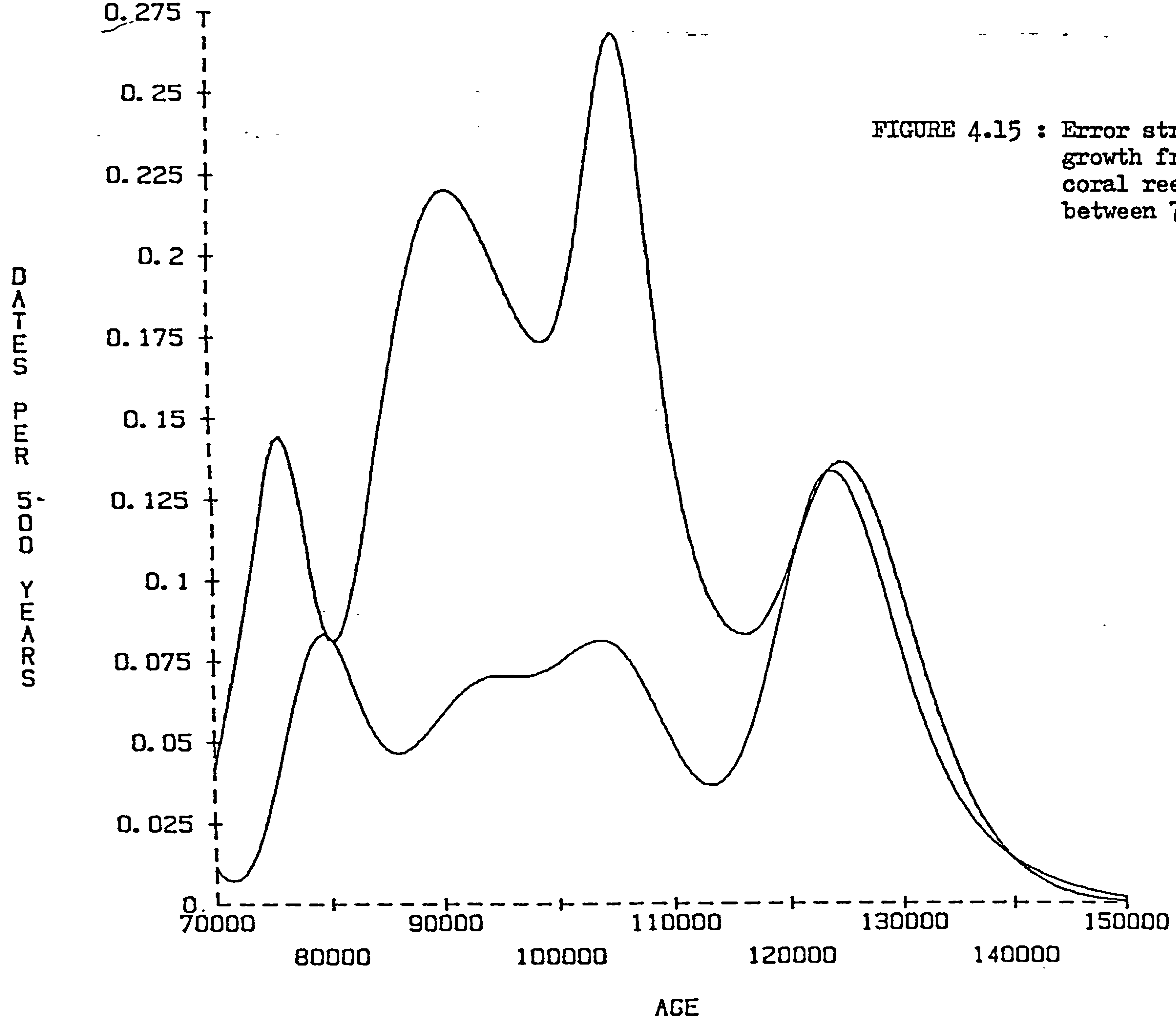


FIGURE 4.15 : Error stripped UK speleothem growth frequency curve and world coral reef date frequency curve between 70000 and 150000 years BP.

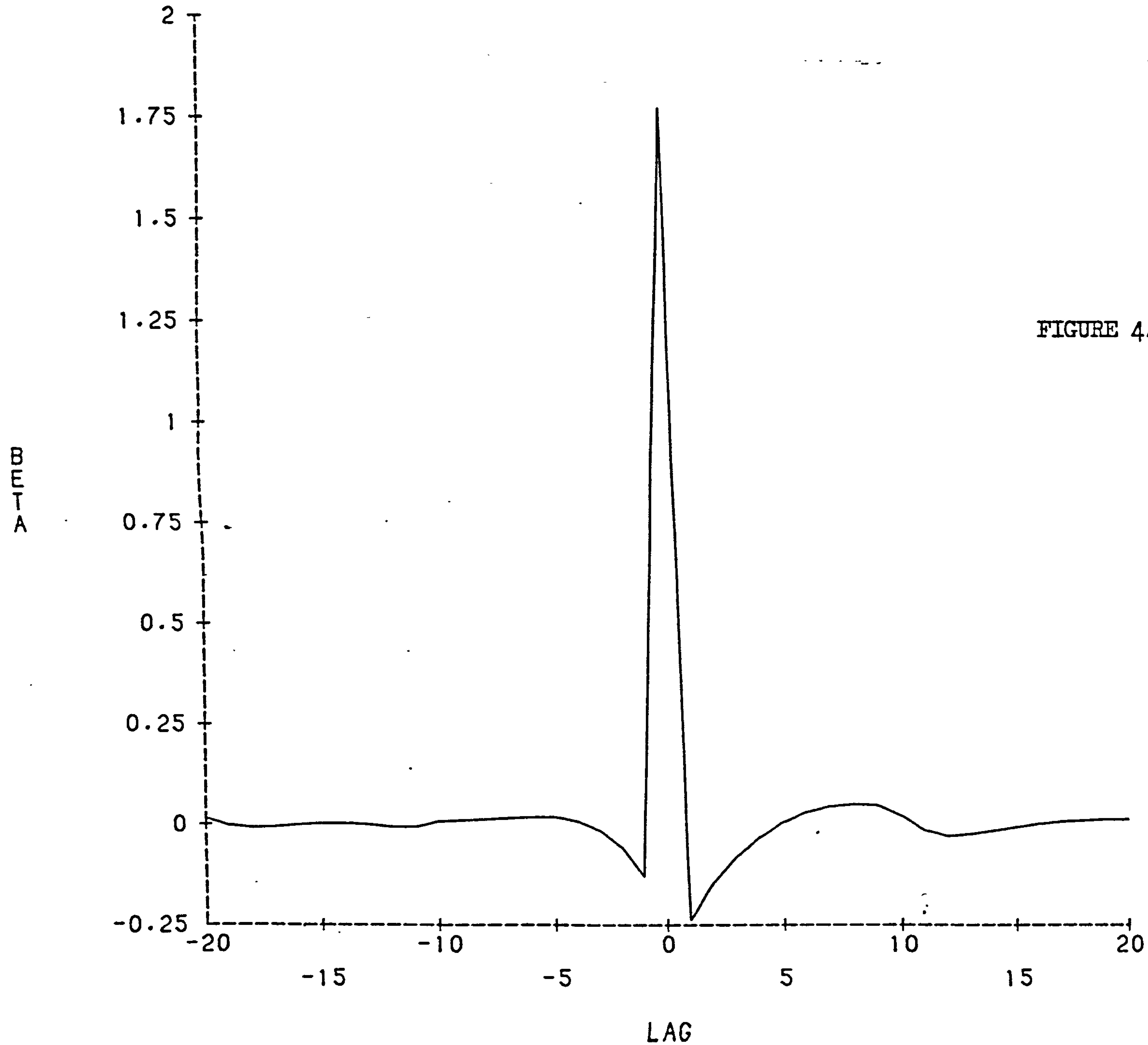


FIGURE 4.16 : Distributed lag cross-correlation between UK speleothem and world coral reef data shown in Figure 4.15.

coherence spectrums yielded similar results, although these cannot be considered as statistically valid as the distributed lag modelling (Dunn 1983 a,b).

This high degree of correlation between speleothem growth periods in the UK and coral reef growth in the tropics and subtropics provides strong evidence for the validity of the distributed error-weighted frequency curve technique and confirms the assumption that UK speleothem growth occurs primarily during interglacial and interstadial conditions which are linked to Milankovitch forcing functions.

Sea Levels, Speleothems and Littoral Sediments

The literature on Quaternary shorelines and littoral sediments of the world is diverse and vast. By 1979 over 8000 articles had been published on Quaternary shorelines alone (Richards & Shapiro 1979). It is beyond the scope of this work to reassess this evidence in the light of the distributed error-weighted frequency curve analysis. Since the purpose of this analysis was to provide an estimate of 'eustatic sealevels' that can be used as an input for future work on isostatic models of sealevel change for the Mendip region. As previously discussed, a knowledge of base level changes along with climatic changes are prerequisites for understanding the present day geomorphology and landscape evolution of the Mendip region. However, the implications of the distributed error weighted frequency curve analysis in both the UK speleothem and world coral reef uranium-series data are considerable for the interpretation of Quaternary events outside the Mendip region. These implications will briefly be discussed with respect to the Mediterranean region which is the classic centre of Quaternary shoreline studies and for the results from the deep sea sediment cores.

The Mediterranean Shorelines

The raised shoreline sequence in the Mediterranean basin influenced the interpretation of sea level studies in the Mendip region for over 50 years. As recently as the mid 1960s researchers aimed to correlate sea level indicators in the Mendip region with those in the Mediterranean on purely altimetric grounds (eg ApSimon *et al* 1961).

Research in the Mediterranean basin during the 19th and early 20th Century established the presence of five elevated shorelines on altimetric grounds, all of which were assumed to be of global importance. They were (Zeuner 1945, 1946):

Stage	Height above sea level
Sicilian	80-100m
Milazzian	55-60m
Tyrrhenian	28-32m
Main Monastirian	18-20m
Late Monastirian	7-8m

The validity of these shorelines was undermined by bio and litho stratigraphic work during the 1950s, which showed that not all beaches at similar level were of the same age (Cuerda 1957, Muntaner-Darder 1957, Gigout 1960). The altimetric approach has now been thoroughly discredited by Hey (1971, 1978), who showed that the preserved horizontal shorelines are essentially random in their vertical distribution. Although the altitudinal evidence is not a conclusive indicator of high sea stands, the biostratigraphical evidence can be. Many of the raised beaches contain an interglacial littoral molluscan assemblage known as the 'strombus' or 'senegal fauna', as several of its characteristic thermophilous elements are currently found only as far north as the Atlantic coast of Senegal. The occurrence of this fauna is indicative of

Mediterranean climatic conditions warmer than the Holocene and presumably with sea levels of similar heights to the present day.

Strombus faunas have been dated directly by uranium-series analysis on molluscan shells (Stearns & Thurber 1965, Lalou *et al* 1971, Butzer 1975, Bernat *et al* 1978) and indirectly by fission track determinations on the Brasalian tuffs west of Rome which are interdigitated with three 'Strombus raised beached' (Bonadonna & Bigazzi 1970, Ambrosetti *et al* 1972). Table 4.6 shows the comparison between the dated 'Strombus' raised beaches and the coral reef growth periods. There is clearly a greater degree of correspondence between the coral record and the Fission track ages of the first, second and third strombus beaches than between the coral record and the uranium-series dated molluscan shells. This is unsurprising considering that Kaufman *et al* (1971) has shown that Mollusca are open systems with respect to uranium-series isotopes and therefore inaccuracies can be expected with ages calculated from them. However, even though the correspondence between the coral reef growth periods and uranium-series 'Strombus' ages is not exact, there is a generally good broad agreement between the two data sets.

The comparison (Table 4.6) clearly shows that the number of high sea stands recognised from the 'Strombus' raised beaches is incomplete with no stands equivalent to peaks sealevels 1-3 being present. This is not surprising considering that these peaks probably represent high sea stands associated with interstadial conditions during the last glacial period. The Strombus faunas only occurred during interglacial conditions warmer than the present day. Therefore the presence of Fission Track and uranium-series dated Strombus faunas that correspond with peaks sealevel 4 (94000 years BP) and possibly sealevel 5 (103000 years BP) gives an unambiguous indication that at least one, possibly two past Eemian/Ipswichian (c.125000 years BP) interglacials occurred in the Mediterranean, and that the interglacial/glacial transition occurred after 90000±18000 years BP. This gives support to the interpretation of the UK speleothem growth period data (see Chapter II) which indicated the occurrence of post Ipswichian interglacials in Britain.

The Deep Sea Sediment Cores

During the latter half of the 20th Century improvements in deep sea sediment coring technology and oxygen isotope analysis techniques (Emiliani 1955) has revolutionised our understanding of Quaternary climatic changes. Early interpretations of O^{18}/O^{16} variations as largely due to oceanic temperature fluctuations (Emiliani 1957, 1966) were superseded by evidence that showed the variations were primarily attributable to global ice volume changes (Shackleton 1967). Shackleton & Opdyke (1973) proposed that a 0.1% decrease in benthic foraminifera O^{18}/O^{16} ratios is equatorial pacific core V28-238 was equivalent to a 10m fall in relative sealevel (Figure 4.17a). However, a number of discrepancies were evident between the isotope record and other sealevel indicators, particularly the arctic strandlines (Williams & Fillon 1981) and the New Guinea coral reefs (Andrews 1982). There is mounting evidence that many factors can and do significantly affect the O^{18}/O^{16} ratios recorded from benthic forams. These have been reviewed by Berger (1979) and Duplessey (1981) and their magnitude estimated (Figure 4.17b). Despite the complexity of the signal recorded by O^{18}/O^{16} variations in benthic forams, high values can be broadly considered to correlate with 'warm' high sealevel conditions and low values with 'glacial' low sea level conditions. Therefore it would be expected that there should be a reasonable degree of correspondence between the deep sea record and the UK speleothem growth record and coral reef growth record. Figure 4.18 shows the oxygen isotope record from deep sea core V19-23 from the Carnegie ridge, South Pacific, which has a high sedimentation rate of 57mm per year, and the composite best estimate UK speleothem growth record. There is reasonably good temporal agreement between these two palaeoclimatic records, particularly the presence of the Ip 1-3 peaks, which it is tempting to correlate with oxygen isotope stages 5A, 5C and 5E.

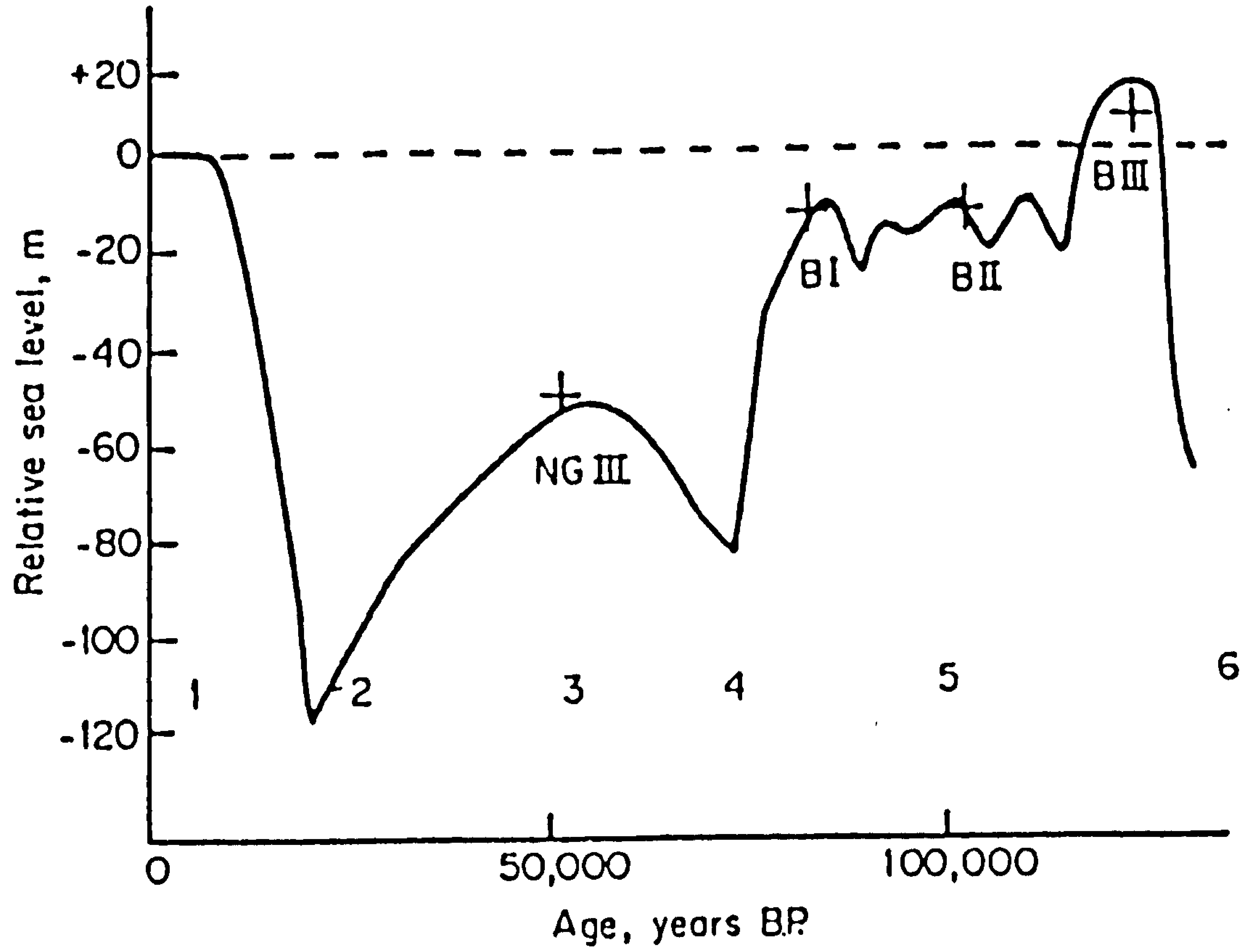
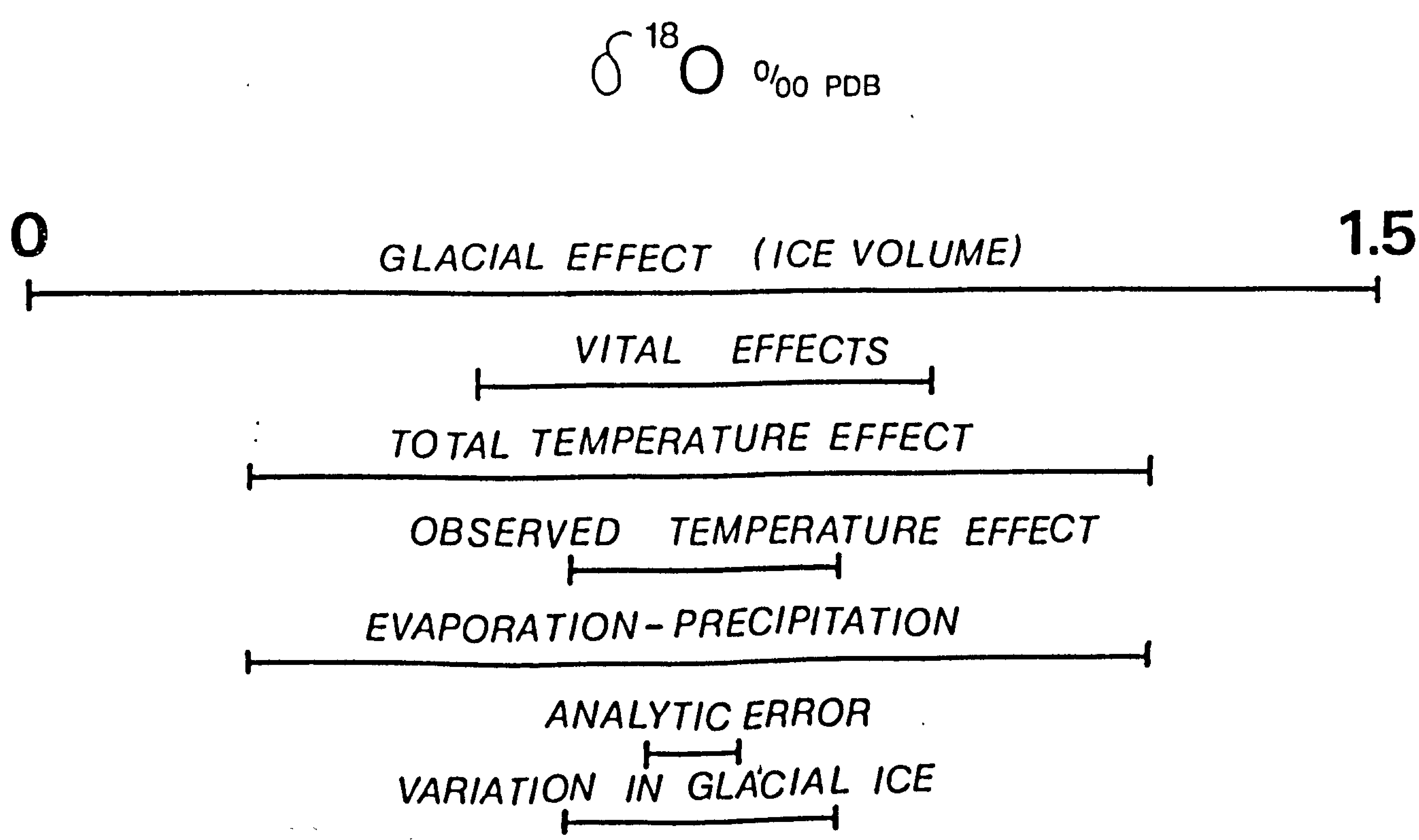


FIGURE 4.17

(A) Upper Pleistocene world relative sea level changes estimated from oxygen isotope analysis of deep sea core V28-238 (Shackleton & Opdyke 1973).



(B) Potential factors influencing the oxygen isotope signal of benthic foraminifers showing the relative magnitude of each with reference to the total 1.5‰ change for a complete glacial–interglacial cycle..

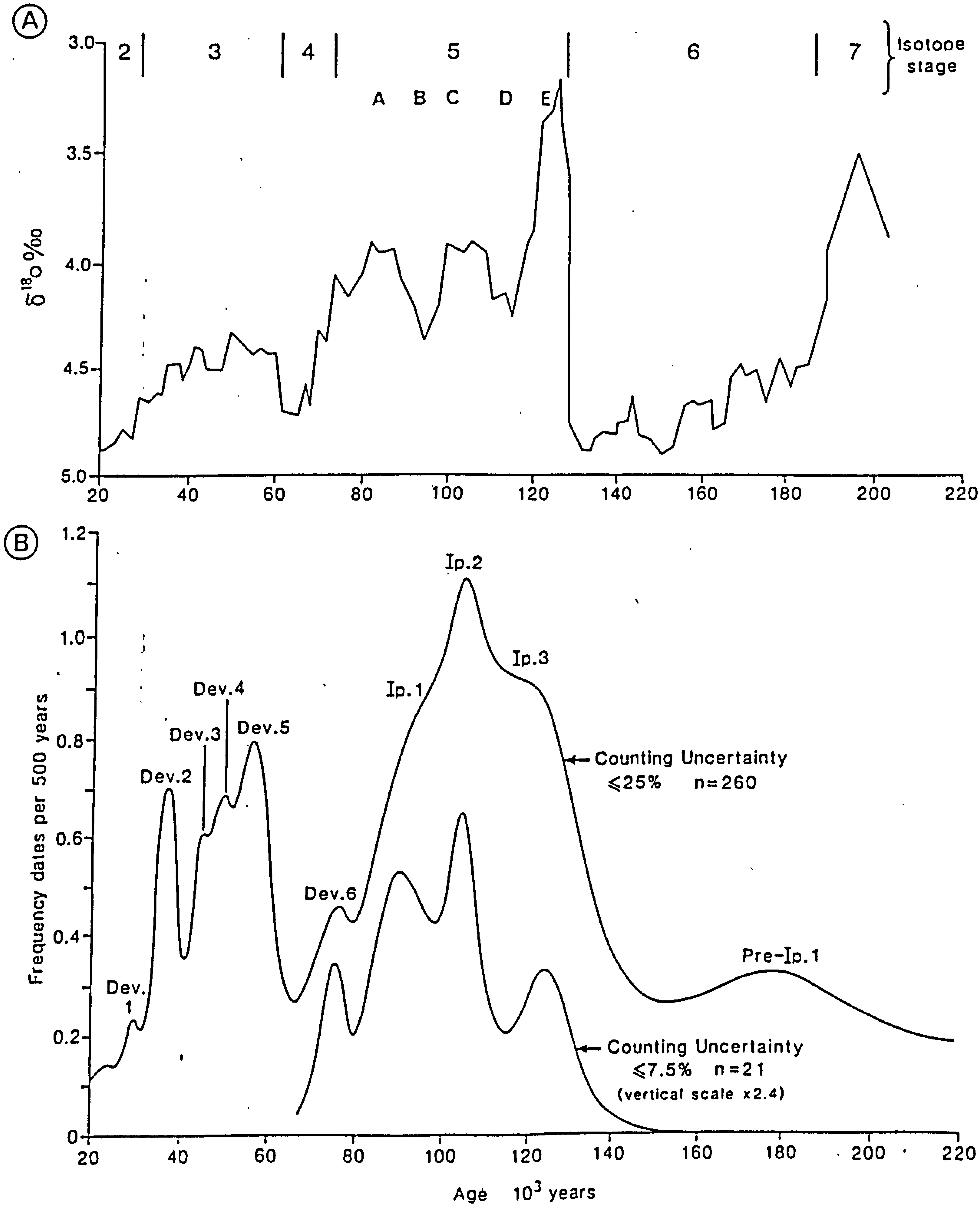


FIGURE 4.18 : Comparison of the oxygen isotope record from deep sea core V19-23 (Ninkovich & Shackleton 1975) with the best estimate UK speleothem growth frequency curve. (Drawn by S. Godden.)

However, there are notable differences between the two records which could be due to three possible causes:

1) The differences in the climatic signal recorded by the two curves and particularly variations in the relative contributions of the factors influencing the O^{18}/O^{16} ratios (see above).

2) The different resolutions of the two records.

3) Inaccuracies in the dating of the records.

A major but seldom discussed limitation on the resolution obtainable from deep sea sediment cores are the effects of bioturbation and sedimentation rate. Schiffelbein (1984) has shown from the amount of 'smearing' of ash and tektites layers from 16 cores with different sediment rates that obtainable resolution is related to sedimentation rate at the -3dβ level (50% loss of signal) by:

$$V = 20/P$$

where

V = sedimentation rate in cm/1000 years^{-1}

P = the period in 1000 years

Therefore to recover a signal of period 4000 years a minimum sedimentation rate of 5cm per 1000 years is required (Schiffelbein 1984). The amplitude and timing of events recorded in deep sea cores are therefore controlled by sedimentation rates. Lower sedimentation rates will yield a smaller glacial O^{18}/O^{16} effect than higher sedimentation rates (Berger 1979) and the relative effects of bioturbation on cores with different sedimentation rates have caused an estimated stratigraphic discrepancy of 4500 years for Termination II c.127000 years BP (Hutson 1980). This stratigraphical discrepancy is independent of the dating uncertainty.

The dating of the deep sea cores has mainly been carried out by fixing absolutely dated points in the O^{18}/O^{16} record and then tweaking the record to Milankovitch isolation curves by spectral analysis (Hays *et al* 1976, Kominz *et al* 1979, Pisias & Moore 1981). However, no account is taken of dating uncertainties of the fixed points. The quality of this dating is best illustrated by reference to the age of the stage 5/4 interglacial/glacial boundary.

Following Suggate (1974) there has been general agreement that the 'last interglacial period' ended between 73000 and 82000 years BP. This age range can be accounted for by the different evidence used to define the last interglacial/glacial boundary, and the different methods of dating employed. For example, McIntyre *et al* (1972) have calculated an age of 73000 years BP (±5000 years BP, Sancetta *et al*, 1972) for a coccolith free zone correlated with carbonate minimum 2. They extrapolated sedimentation rates based on ^{14}C dated sections of 3 deep sea cores and interpolated between the ^{14}C dates and an assumed age of 127000 years BP for carbonate minimum 3, based on a correlation of minimum 3 with the uranium-thorium dated termination II of Broeker and van Donk (1970). However, Ninkovich and Shackleton (1975) have demonstrated that the carbonate dissolution record lags the oxygen isotope record by an average 5000 years in deep sea cores. Allowing for this lag the oxygen isotope stage 5/4 boundary which Kukla and Baskin (1983) have argued marks the onset of a full glacial environment, would be placed at 78000±5000 years BP.

The estimated age of the stage 5/4 boundary also varies depending on the method used to calculate it. Ninkovich *et al* (1978) have obtained 2 potassium-argon dates on the Torba Tuffs in Sumatra of 73000±3000 and 74900±12000 years BP. These tuffs have been mineralogically correlated with an ash layer which intersects the stage 5/4 boundary, in core RC14-37. In core V28-238 Shackleton & Opdyke (1973) calculated an age of 75000 years BP for this boundary, by assuming a uniform sedimentation rate between the top of the core and the Brünhes/Matuyama boundary, dated at 700000. Recent more accurate determinations of the half lives of potassium and argon have led to the reassignment of the age of the Brünhes/Matuyama boundary to 730000 years BP (Mankinen & Dalrymple 1979, Berggren *et al* 1980). The recalculated age of the 5/4 boundary assuming uniform sedimentation rates in V28-238 is therefore 78000 years BP. Correlation between the oxygen isotope record and the Milankovitch orbital parameters yielded an age of 73000 years BP (Hays et al 1976, Komintz et al 1979), while assuming a constant aluminium accumulation rate up to the Brünhes-Matuyama boundary obtained an age of 80400 years BP. Finally direct dating of V28-238 by ^{230}Th continuous strip sampling gave an age of 81600±4100 years BP.

This Ionium date agrees well with the evidence of a marked decrease in speleothem deposition around 80000 years BP (Figure 3.7). The bulk of the deep sea core dating evidence suggests that this is a more reliable age for the last glacial/interglacial boundary than the commonly accepted age of 73000 years BP.

It is clear from this discussion and the comparison of the UK speleothem growth curve and the deep sea core oxygen isotope curve (Figure 4.18) that the UK speleothem growth curve provides the more securely dated and higher resolution record of climatic fluctuation during the upper Pleistocene. The effects of bioturbation in the deep sea cores means that only low frequency high magnitude events such as interglacial/glacial cycles can be reliably detected. High frequency low magnitude signals such as interstadial/stadial cycles are only rarely resolved even in cores with high sedimentation rates.

Conclusion

1) Advanced in our understanding of earth rheology and the responses to glacial and hydrological loading has invalidated much of the earlier work on Quaternary shore line correlations in the Mendip region based upon altitudinal correspondence.

2) Studies on littoral deposits have yielded useful sedimentological and palaeoenvironmental information but little of chronostratigraphic importance.

3) Attempts at relative dating by means of amino acid racemization studies on sub-fossil mollusca have demonstrated the promise of this technique but this has not yet been fully realised.

4) The necessity of reconstructing base level changes in order to understand the present day geomorphology and landscape evolution of the Mendip region requires that broad eustatic curves are estimated in order to calculate the likely region specific sealevel changes.

5) The high sea stand record is incomplete and poorly understood in the Mendip region due to its slow rate of tectonic uplift and the lack of datable deposits.

6) A more complete record of large scale sealevel changes is preserved in the coral reef terraces in many tropical and sub-tropical regions.

7) Periods of high sea stands in the tropics and sub-tropics correspond with periods of speleothem growth in the UK, confirming the reliability of these records and the influence of Milankovitch forcing functions on both these palaeoclimatic indicators.

8) Uranium-series dated speleothem and coral reef growth records are consistent with the results of potassium argon dating on the Strombus raised beaches in the Mediterranean, which is the classic area for Quaternary shoreline studies.

9) The speleothem and coral reef growth records are consistent with the deep sea core oxygen isotope curves. However, they provide a better dated and higher resolution record of upper Pleistocene climatic fluctuations than do even the most rapidly sedimented deep sea cores.

S E C T I O N 1

SUMMARY AND CONCLUSION

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The purpose of studying the Mendip speleothem growth record was threefold:

(1) to determine if useful palaeoclimatic information can be obtained from this record;

(2) to provide an absolute stratigraphic framework within which Quaternary fossiliferous sites can be interpreted;

(3) to demonstrate that Pleistocene climatic fluctuations recorded in the Mendip region were not parochial events but had global influence.

Chapter II discussed the theoretical background of speleothem deposition and the statistical analysis of uranium-series data. There is good evidence for assuming that in the UK, speleothem deposition will occur predominantly during interglacial and interstadial periods and virtually cease when stadial climatic conditions prevail.

Chapter III demonstrated that the distributed error-weighted frequency curve technique of Gordon & Smart (1984) and Gordon *et al* (1987) could be used to identify UK speleothem growth periods during the Upper Pleistocene. Nine such periods are identified and the absolute dating evidence from both uranium-series dated fossiliferous sites and TL dated periglacial deposits was shown to be consistent with the interpretation that speleothem growth occurred primarily during 'warm' periods. The most important implications of this finding are:

(1) The 'pollen based' UK Upper Pleistocene stratigraphy is incomplete with fewer 'warm' periods having been identified than occurred.

(2) Between 80000 to 130000 years BP there were three periods of interglacial conditions, not one, as has been assumed from the pollen-based record. This is the first time that three distinct Upper Pleistocene interglacials have been recognised from terrestrial UK deposits.

(3) The last interglacial/glacial boundary has been absolutely dated for the first time in the UK to be c.80000 years BP.

(4) The importance of Milankovitch forcing functions in controlling Quaternary climatic fluctuations was confirmed.

Chapter IV discussed the Mendip sealevel record and determined that much of the past work was based upon the false premise of Eustasy. Mathematical solutions appear to yield the best hope for reconstructing past sealevel changes in the Mendip region as long as accurate boundary conditions can be supplied to the model. However there are good *a priori* reasons for assuming that only a very incomplete record of past sea levels will have been preserved in the Mendip region. A more complete record is preserved by the raised coral reefs in tropical and sub-tropical regions which can be uranium-series dated. A modified version of the distributed error-weighted frequency curve technique has identified seven periods when sea levels were significantly high on a global scale, although their exact height varies from region to region as had been expected. The ages of these periods of high sea levels correspond well with fission track dates on Mediterranean interglacial beach deposits and with the oxygen isotope deep sea core record, although there are specific

differences with the deep sea record which largely result from the limited resolution and inadequate dating of the Upper Pleistocene section of this record.
The reliability of both the UK speleothem and the coral reef record was established by cross-correlation analysis which established at better than the 1% significance level that active speleothem deposition was occurring in UK caves during the same periods that coral reef growth was occurring in the tropical and sub-tropical regions of the world.

Table S1.1 summarises all the important correlations described in Section 1 (Chapters II, III and IV). Considering the range and coverage of these diverse data sources, the degree of correspondence is remarkable. Periods of speleothem growth in UK caves as identified by uranium-series dating occur virtually simultaneously with

(1) periods of increased solar insolation as dated by celestial mechanics;

(2) periods of coral reef growth relating to high sea levels in the tropics and sub-tropics as dated by uranium-series analysis;

(3) interglacial beach formation in the Mediterranean dated by fission track dating of interdigitated volcanic tuffs;

(4) warm sea surface temperatures in the Atlantic off the west coast of Ireland as determined by the foram analysis of Sancetta *et al* (1973) and dated by standard deep sea core chronology;

(5) periods of low UK speleothem growth corresponding with periglacial loess deposition, solifluction and ice wedge growth in north west Europe as dated by thermoluminescence dating.

TABLE S1.1 : COMPARISON OF UK SPELEOTHEM GROWTH RECORD WITH OTHER CLIMATIC INDICATORS

UK Speleothem Record Peak	UK Speleothem Record Age	Global warming based on astronomical forcing after Mörner 1972 Age	Global warming based on astronomical forcing after Mörner 1972 Nature & Period	World Coral Reef Record Peak	World Coral Reef Record Age (arrows indicate direction of true age)	Fission-Track Ages of the 'Strombus' raised beaches in the Mediterranean	TL ages of periglacial sediments in the UK, Denmark and France	Age estimates of warm summer and winter sea surface temperatures from Atlantic deep seacore V23-82	Summer sea surface temper- -ature (Modern = 15°C)
		23000					14500 to 24000		
Dev 1	29500	↓	Interstadial					31000	10,5
		↓	Complex						
		32000							
Dev 2	36000	?							
		40000					39000±5000		
		↓							
Dev 3	45000	↓	Interstadial	Sealev 1	43000				
		45000							
		47000							
Dev 4	50000	↓						48000	12,1
		↓	Interstadial		↑				
Dev 5	57000	↓		Sealev 2	63000			59000	9,6
		60000							
		72000					75000±6500		
		↓	Interstadial		↑				
Dev 6	76000	↓		Sealev 3	78000				
		83000							
		83000					80000±7000		
		↓	Stad/Intersta-		↑				
IP 1	90000	↓	dial/Stad	Sealev 4	92000	90000±18000		81000	15,2
		94000							
		94000							
IP 2	105000	↓	Interglacial	Sealev 5	103500				
		105000			↓				
		116000					114000±1600		
IP 3	124000	↓	Interglacial	Sealev 6	124000	127000±10000		124000	16,0
		128000					132000±11000		
PRE-IP 1	180000			Sealev 7	173000	177000±30000			

This degree of correlation between these diverse data sets cannot be coincidence. They provide overwhelming evidence for the theoretical arguments that speleothem growth in the UK occurs predominantly during interglacials and interstadials. The distributed error-weighted frequency curve technique of Gordon & Smart (1984) and Gordon *et al* (1987) permits the construction of a continuous absolutely dated terrestrial record of Quaternary climatic fluctuations during the Upper Pleistocene which is of higher resolution and more accurately dated than any other terrestrial or marine climatic record. The speleothem record thus provides the best available stratigraphic framework within which to interpret Quaternary deposits in the Mendip region and elsewhere in Britain.

S E C T I O N II

THE FAUNAL RECORD

CHAPTER V

THE FAUNAL RECORD : POTENTIAL AND PROBLEMS

Introduction

The Quaternary stratigraphy of Britain rests mainly on biostratigraphical correlations between fossiliferous deposits (Mitchell *et al* 1973). During the nineteenth and early twentieth centuries knowledge of Quaternary climatic change, hominid evolution and prehistory was gained predominantly from the excavation of cave sediments (Campbell 1977, Colcutt 1985). Boyd-Dawkins wrote in 1884 *"The exploration of caves is rapidly becoming an important field of enquiry and their contributions to our knowledge of the early history of the sojourn of men in Europe are daily increasing in value and in number."* However, the advent of plant macrofossil and pollen analysis led to a world-wide decline of interest in cave sediments, except in France where there has remained a strong tradition of cave research. During the 1960s and early 1970s the predominance of the 'Cambridge' school in British Quaternary studies led to the virtual eclipse of interest in Quaternary research in British caves. West's classic textbook *Pleistocene Geology and Biology* (1968) makes only brief reference to caves, whereas Sparks & West (1972) state *"Open habitation sites...contrast with cave sites where the stratigraphy is often far more complex and difficult...the regional environment is more difficult to study under these conditions, especially in the absence of well-preserved fossils of the kind we find associated with open sites and organic deposits."*

Sparks & West (1972) thereby perpetrated the myth that fossils are often badly preserved in cave sediments. This is clearly untrue with respect to vertebrate and molluscan remains: over 100 sites with well preserved fossil vertebrate faunas are known from the Mendip region (the most reliable are listed in Appendix 2) and over 20 with molluscan faunas (Willing 1985). Insect remains are rarely preserved in cave sediments except as impressions in tufacious speleothem in entrance deposits (eg Gough's and Elderbush caves), however, pollen is frequently found preserved in a whole range of cave sediments (Campbell 1971, 1977; Hunt & Gale 1986; Leroi-Gourhan 1985) although few serious studies have been undertaken in Britain until recently.

The relative neglect of cave sites has been detrimental to the development of an accurate UK Quaternary stratigraphy. The primacy of the pollen record has often led to attempts to squeeze additional warm periods recognised from fossil vertebrate remains into the incomplete pollen stratigraphy. Thus the 20 metre sequence of calcareous sediments at Westbury-sub-Mendip has been correlated with just a single stage of the Cromerian interglacial (Cr iv) solely on the basis of a correlation with the vertebrate fauna at Ostend. Pollen from the sediment matrix adhering to some of the Ostend specimens was indicative of coniferous forest vegetation with some middle Pleistocene elements (Stuart & West 1976). This minor palaeonological evidence has led Stuart (1982,1983) to disregard the substantial weight of fossil vertebrate evidence for a new middle Pleistocene interglacial (Bishop 1982) and the sedimentological unlikelihood of such a thick and complex sequence of sediments forming in just 2000-3000 years (see Chapter IX).

Likewise, despite ample evidence from fossil vertebrate faunas of more than one warm stage during the 'last interglacial period' (Sutcliffe 1975,1976,1985; Sutcliffe & Kowalski 1976), the inability to separate these stages in the UK pollen record has led to many fossil vertebrate sites being possibly erroneously assigned to Ipswichian interglacial stages (Stuart 1976;1983), even when the palaeoenvironmental information inferred from fossil vertebrate faunas is at variance with the climatic conditions associated with the pollen spectra of a given stage - for example the assignment Crayford site with its 'steppe' vertebrates of muskox, woolly rhinoceros, susliks and lemmings to zone 4 of the Ipswichian (Stuart 1976, 1983) which is characterised by open coniferous forests (Phillips 1974). Since the geomorphology of the Crayford site indicates that it is older than the Thames ' hippopotamus fauna' sites of Ipswichian zone IIb age (Sutcliffe 1976, 1985), the likelihood of the Crayford steppe fauna being of an Ipswichian age is small.

As discussed in Chapters III and IV the 'last interglacial period' was characterised by three warm stages with associated high sea levels. These three warm periods are not currently separable in the UK pollen record but may be detectable in the fossil vertebrate record. However, interpretations of the age of fossil vertebrate sites have in the past been heavily influenced by the pollen stratigraphy despite the fact that the vertebrate record may in some circumstances be more complete than the pollen record. It is therefore necessary to re-examine the Mendip fossil vertebrate sites in the light of both the absolute chrono-stratigraphic framework provided by the statistical analysis of uranium-series dated speleothems and also in relation to the biostratigraphic record of other UK Pleistocene vertebrate sites.

Potential of the Mendip Fossil Vertebrate Record

The number of fossil vertebrate sites and the quantity of material recovered from them makes the Mendip region one of the richest areas in Europe in which to study Quaternary faunal changes. Unfortunately two major factors make this task difficult: firstly the state of Pleistocene vertebrate palaeontology as a science in Britain, and secondly the contaminated nature of much of the Mendip fossil vertebrate material which results from the poor stratigraphic control of most of the excavations which occurred during the nineteenth century.

Quaternary Vertebrate Palaeontology in Britain

In 1969 the editors of *Nature* derided all palaeontology as a false science that sought no synthesis and fragmented into small groups of experts who studied less and less (Gould 1980). They wrote: *"Scientists in general might be excused for assuming that most geologists are palaeontologists and most palaeontologists have staked out a square mile for their life's work. A revamping of the geologist's image is badly needed."* (Anon 1969)

However, during the past 20 years palaeontology has been revolutionised by the advent of palaeobiological studies which has transformed palaeontology from being primarily concerned with the study of taxonomic description into a science used to test the fundamental problems of biology in such diverse topics as evolution theory, ecology, population biology and functional morphology (Gould 1981). The number of palaeontology papers and periodicals has dramatically increased over the past ten years - although this revolution has not yet had a significant effect on Quaternary vertebrate palaeontology in Britain, despite the fact that the quality and resolution of the UK Pleistocene record is vastly superior to the fossil sequences from any other geological periods. This should in no way be construed as a criticism of the few UK researchers whose primary interest is Quaternary vertebrate assemblages. Since the 1950s none of the handful of specialist workers in this field has had a tenured post at a university or polytechnic for more than a brief period. All major studies of UK Pleistocene vertebrates have been undertaken either by museum staff or research students whose other commitments have seldom allowed them to undertake the lengthy research that is often required for palaeobiological studies. This situation is unique to British Quaternary vertebrate palaeontology; all other areas of Quaternary palaeobiology have received continued research support which has allowed long-term research projects to be undertaken.

Although advances have been made in vertebrate biostratigraphy and taxonomy, our understanding of UK Quaternary vertebrate palaeobiology is limited and mainly derives from analogies with continental studies or from contemporary biological research. However, despite the limited state of current knowledge the potential for advance is huge, particularly in the fields of quantitative palaeoclimatology and palaeoecology.

Vertebrate Assemblages and Quantitative Palaeoclimatology

Quaternary vertebrate assemblages (with the exception of small rodent assemblages) have often been considered in the UK to have little useful palaeoclimatic potential (Currant 1985), since they largely consist of mammals which, due to their endothermy, are less influenced by direct climatic factors than lower vertebrates or invertebrates (Stuart 1982) However, a range of climatic factors are known to be important in limiting the range and distribution of a given species frequently through indirect mechanisms, eg by confirming a strong competitive disadvantage compared to better adapted animals. Several quantitative palaeoclimatic studies have been carried out on continental Quaternary fossil vertebrate assemblages. These studies have assumed that the distributions of several species of mammals are in equilibrium with present day climatic conditions and that similar climatic limitations influenced their past distributions. Early work by Hokr (1951) and Fabre (1970) was flawed by the limitations of the material available to them, although they demonstrated the potential of this type of analysis. Bonifay (1982) has shown that useful palaeoclimatic information can be obtained even from large fossil mammal assemblages, particularly from Artiodactyles. Climatic thresholds were determined by comparing the actual distributions of those large present day European mammals that are thought to still have approximately natural distributions with the climatic maps of Europe. Using these data Bonifay (1982) made quantitative estimates of seasonal variations in temperature, evapotranspiration and continentality between 18000 BP and 10000 BP in the south of France, which were in good agreement with other independent climatological indicators.

Table 5.1 shows the climatic thresholds of a selected range of mammals that still have present day palaeoarctic distributions and are found as fossils in the UK Pleistocene deposits. The thresholds are either from Bonifay (1982) or were calculated by comparing the mammal distribution maps of Corbet (1978) with the WMO/UNESCO climatic maps (1970, 1981) and cross checking against the relevant climatic station data listed in Müller (1983). These climatic thresholds should therefore be considered as preliminary estimates which could be refined if higher resolution distributional and climatic data were used.

It is clear that useful palaeoclimatic information can be inferred by the fossil presence of certain species in most mammalian orders and not just Rodentia or Artiodactyla. All the commonly represented mammalian orders contain 'cosmopolitan' species that are tolerant of a wide range of climatic conditions but also 'specialist' species that appear to be limited by various climatic thresholds. However, climatic thresholds cannot be calculated by this distributional range method for many species of commonly occurring fossil mammals whose distributions have been markedly influenced either by human activity or historical accident. This is particularly problematic with most carnivore species (eg Lion, Leopard, Wolf) but also with many other large mammals (eg Hippopotamus, Bison, Horse) whose distributions are known to have significantly contracted as human populations have expanded (Corbet 1978; Dorst & Dandelot 1970). Likely climatic thresholds can be inferred for many of these species from direct ecological and population biology studies (see Chapter VII).

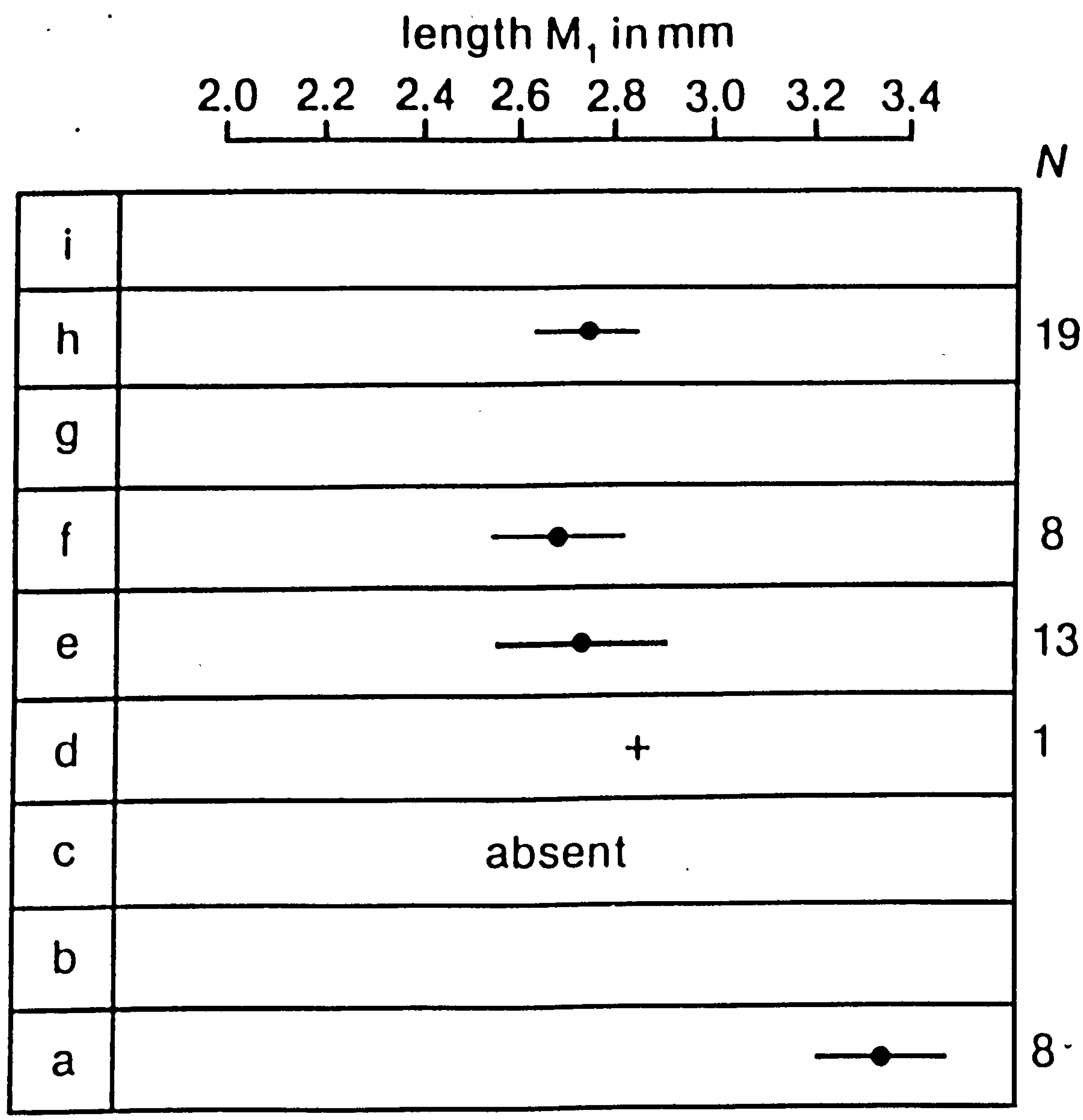
TABLE 5.1 : ESTIMATED CLIMATIC THRESHOLDS OF SELECTED MAMMALS WITH A PRESENT DAY PALAEOARCTIC DISTRIBUTION

MAMMAL SPECIES	Mean Annual Precipitation Range in mm	Extreme Mean January Temperature in °C	Extreme Mean July Temperature in °C	Mean Annual Temperature Range in °C	Number of Days when Vegetation Growth is Possible (Days >5°C)	Mean Annual Evotranspiration Range in mm
Insectivora						
Erinaceus europaeus (Hedgehog)	300-2000	-20	+27	35		
Talpa europaea (Mole)	500-3000	-17	+22	37,5		
Desmana moschata (Russian Desman)	200-500	-12,5	+25	37,5		
Lagomorpha						
Oryctolagus cuniculus (Rabbit)	500-2800	-3	+23	27,5		
Lepus timidus (Mountain Hare)	200-3000	-50	+23	65		
Ochotona pusilla (Steppe Pika)	200-500	-22	+25	40		
Rodentia						
Spermophilus sp. (Susliks)	100-600	-47	+30	55		
Dicrostonyx torquatus (Arctic Lemming)	100-500	-40	+12,5	50		
Lemmus lemmus (Norway Lemming)	100-2000	-40	+12,5	47		
Clethrionomys glareolus (Bank Vole)	300-2000	-20	+25	45		
Arvicola terrestris (Water Vole)	200-2000	-35	+27	40		
Microtus arvalis (Common Vole)	350-1600	-28	+25	40		
Microtus agrestis (Field Vole)	350-2000	-35	+20	45		
Microtus oeconomus (Northern Vole)	200-800	-45	+30	62		
Microtus gregalis (Tundra Vole)	200-2000	-37	+25	45		
Apodemus sylvaticus (Wood Mouse)	300-2500	-27	+30	45		
Carnivora						
Alopex lagopus (Arctic Fox)		-70	+12,5	65	100	300-2000
Ursus arctos (Brown Bear)	200-2000	-60	+35	65		
Artiodactyla						
Sus scrofa (Wild Boar)		-30	+30	50	150	200-700
Cervus elaphus (Red Deer)		-35	+25	50	125	300-700
Capreolus capreolus (Roe Deer)		-40	+30	50	125	200-700
Rangifer tarandus (Reindeer)		-70	+17	65	0	300-700
Saiga tartarica (Saiga Antelope)		-20	+28	45	160	100-700

The significance of the results in Table 5.1 for our interpretation of the likely prevalent palaeoclimatic conditions of many Mendip sites will be discussed in Chapter VII. However there are two lines of research that could significantly refine the results of fossil vertebrate palaeoclimatic studies. Recently Atkinson *et al* (1987) have demonstrated the utility of their Mutual Climatic Range (MCR) technique in using coleoptera assemblages to reconstruct palaeoclimatic conditions in Britain over the past 22000 years BP. They calculated a continuous curve of the likely average value and range of the mean maximum annual temperature, mean minimum annual temperature, and the mean annual temperature by using a modified version of the distributed error weighted frequency curve technique of Gordon & Smart (1983) on radiocarbon dated coleoptera sites (T Atkinson *pers comm*). The MCR technique could be applied to the fossil vertebrate data, particularly since modern vertebrate distributions are better recorded than coleoptera distributions.

Detailed palaeoclimatic information may also be obtainable from morphological studies on certain fossil species. For example temperature is known to cause a number of phenotypic changes in mice that have morphological expressions (Harrison 1958; Harrison *et al* 1959). Winter mortality in the house mouse (*Mus musculus*) has been shown to be temperature dependent (Berry 1978), causing both heterozygosity and non-metrical-skeletal variation to be markedly reduced in winter months (Berry & Jackson 1975; Berry & Peters 1976). Likewise brain case size in the common shrew (*Sorex araneus*) varies seasonally, being smaller in winter than in summer (Crowcroft & Ingles 1959). Many species (including large mammals) exhibit gross morphological size reductions in response to increasing temperature (Bergman's Law), although the response is often complex (Scholander 1955,1956; Hardy 1979). This type of variation is well documented in Pleistocene European mammals (see Figure 5.1), although no attempt at quantification of the palaeoclimate has been made from these data (Kurten 1968).

FIGURE 5.1 : Size changes in the Norther Vole (*Microtus oeconomus*) at Bacon Hole Cave, Gower (Stuart 1982).



Advances in multivariate techniques have made possible the identification of small mammal species in Bacon Hole Cave, Gower Peninsula, from post cranial skeleton material (Graham & Saunders 1978), which makes possible studies of detailed non-metrical variation. However no quantitative palaeoclimatic studies have yet been attempted from these or other data from UK sites (Brothwell & Jones 1978).

Palaeoecology

Numerous palaeoecological reconstructions of UK Quaternary environments have been undertaken using fossil pollen (eg Godwin 1975; Pennington 1974), Mollusca (eg Kerney 1977), and Coleoptera (eg Coope 1977). By contrast detailed palaeoecological reconstruction based on fossil vertebrate faunas are relatively scarce (Turner 1981, Stuart 1982). This is somewhat surprising considering the size of the literature on present day mammal ecology. Detailed natural history observations exist on most British mammal species dating back to the 17th Century (Allen 1976). This is supplemented by detailed ecological studies on most species during the past century (Corbet & Southern 1977) and during the past 25 years radiotracking and infra red observation techniques have allowed the 'complete' ecologies of small populations of certain mammal species to be reconstructed (Corbet & Southern 1977). It is probably no overstatement to say that we know more about the ecology of a number of individual species of mammal than we do about entire genera of mollusca and coleoptera species. (This would be untrue with respect to plants; however fossil pollen studies usually only allow identification to the genus level.)

Recent work has demonstrated the potential of quantitative palaeoecological studies (Wells 1978). Turner (1981) has measured fossil material from most of the large mammals in several Mendip caves and recorded their size variations, although some of the conclusions he draws from these data are open to interpretation due to problems with the stratigraphic framework in which he placed these sites (Stringer & Currant 1981). Turner (1981) has attempted life table analysis on hyaena fossils from a number of Mendip caves (Figure 5.2). The age at death classes were based upon the amount of tooth wear. The results from Wookey Hole, Uphill and Pickens Hole are comparable to those from modern hyaena populations in the Serengeti, which are under no ecological stress due to an abundance of prey. By contrast modern hyaena populations in Ngorangoro Crater exhibit high rates on infant mortality due to lack of prey species (Kruuk 1972). The Sandford Hill distribution is comparable to those found from 'lying up' areas rather than from dens (Turner 1981).

The power of life table analysis for identifying "favourable" and "unfavourable" ecological conditions has been demonstrated from both sub fossil (Deevey 1947) and Pleistocene fossil material (Kurten 1976).

The application of biological statistics such as diversity indices to fossil vertebrate remains has enabled unbiased and more accurate palaeoclimatic reconstructions. Andrews,P. *et al* (1979) have shown that species diversity can be used to identify past environments even from fossil mammalian faunas which are composed exclusively of extinct species. This approach removes the dependence on the use of single species or groups of species as environmental indicators. A commonly used methodology that *"not only excludes evidence from the rest of the fauna but also carries the assumption that somehow or other the authors know the habitat preferences of extinct animals"*(Andrews *et al* 1979). Gordon & Ellis (1985) have demonstrated that by combining the results of life table analyses with biological meaningful diversity indices (Goodman 1975) such as those proposed by Hurlbert (1971), it is possible not only to distinguish large and small scale environmental fluctuations from random noise, but also to calculate changes in sedimentation rates. The techniques of Gordon & Ellis (1985) were applied to Flandrian fossil mollusca (Figure 5.3). However they would be equally

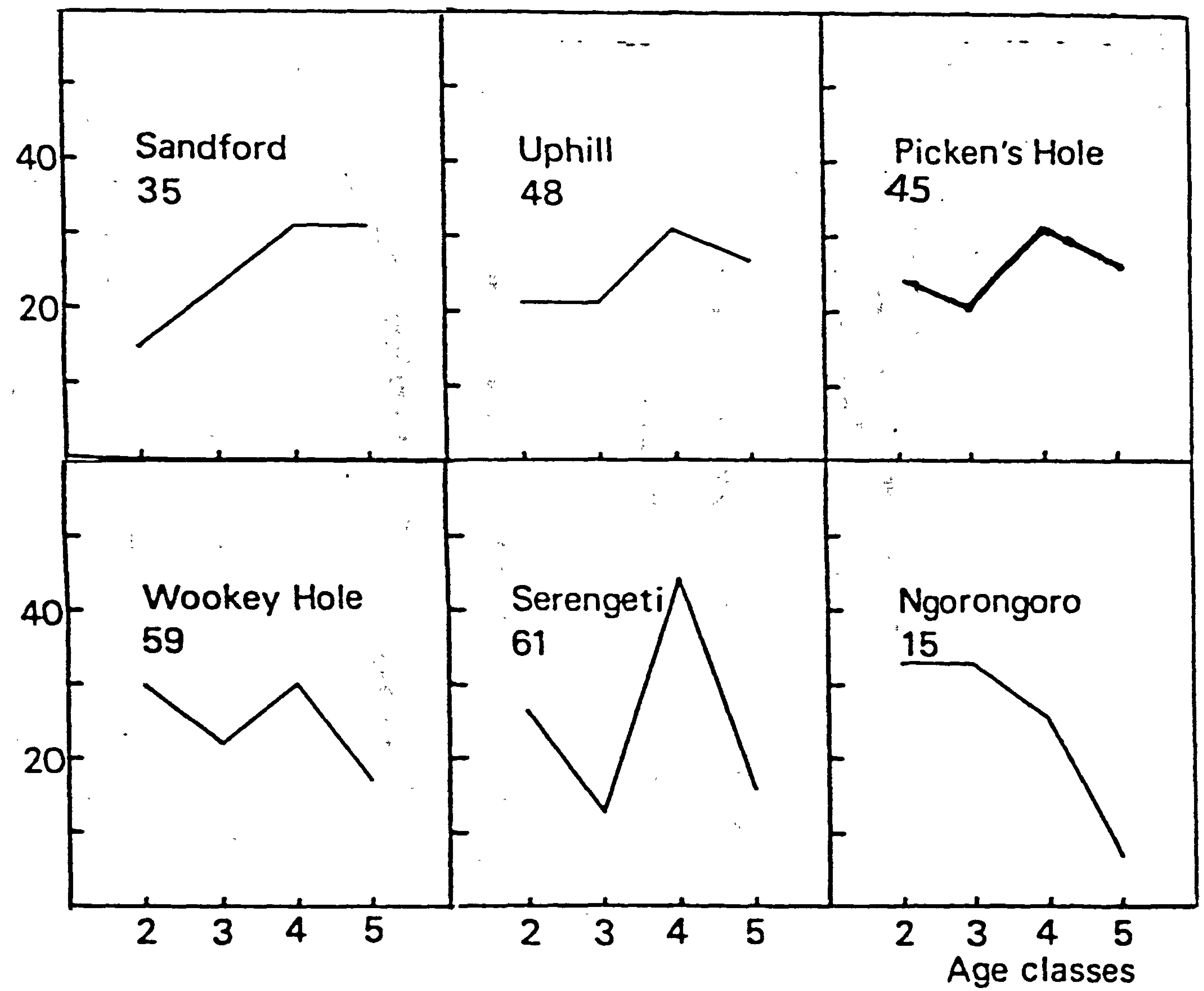


FIGURE 5.2 : Age at death of modern and fossil hyaenas (adapted from Turner 1981).

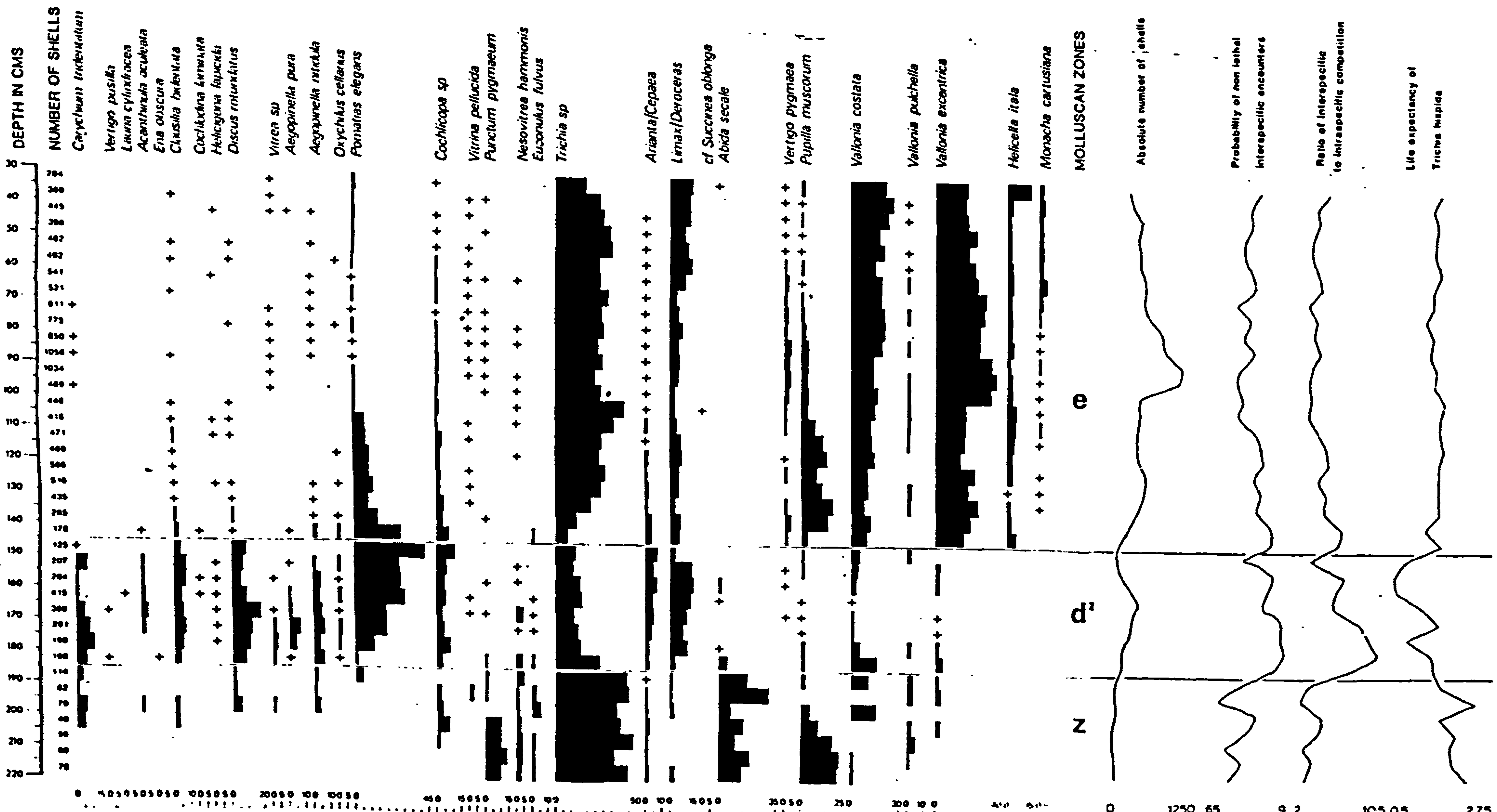


Fig. 5.3 Molluscan data, Asham Quarry (Gordon & Ellis 1985).

applicable to high resolution fossil vertebrate data such as that of Brothwell & Jones (1978) (Figure 5.4). Unfortunately no data of this quality is currently available from any Mendip sites, although it will become available when the results of Picken's Hole and Westbury-sub-Mendip excavations are finally published.

The potential of palaeoecological reconstruction based upon fossil mammal faunas is good. Attempted reconstructions in the Mendips are discussed in Chapter VII based on the data analyses in Chapter VI. These reconstructions are by necessity incomplete since the size of the mammalian ecology literature precludes a complete study, which could be the work of several PhDs.

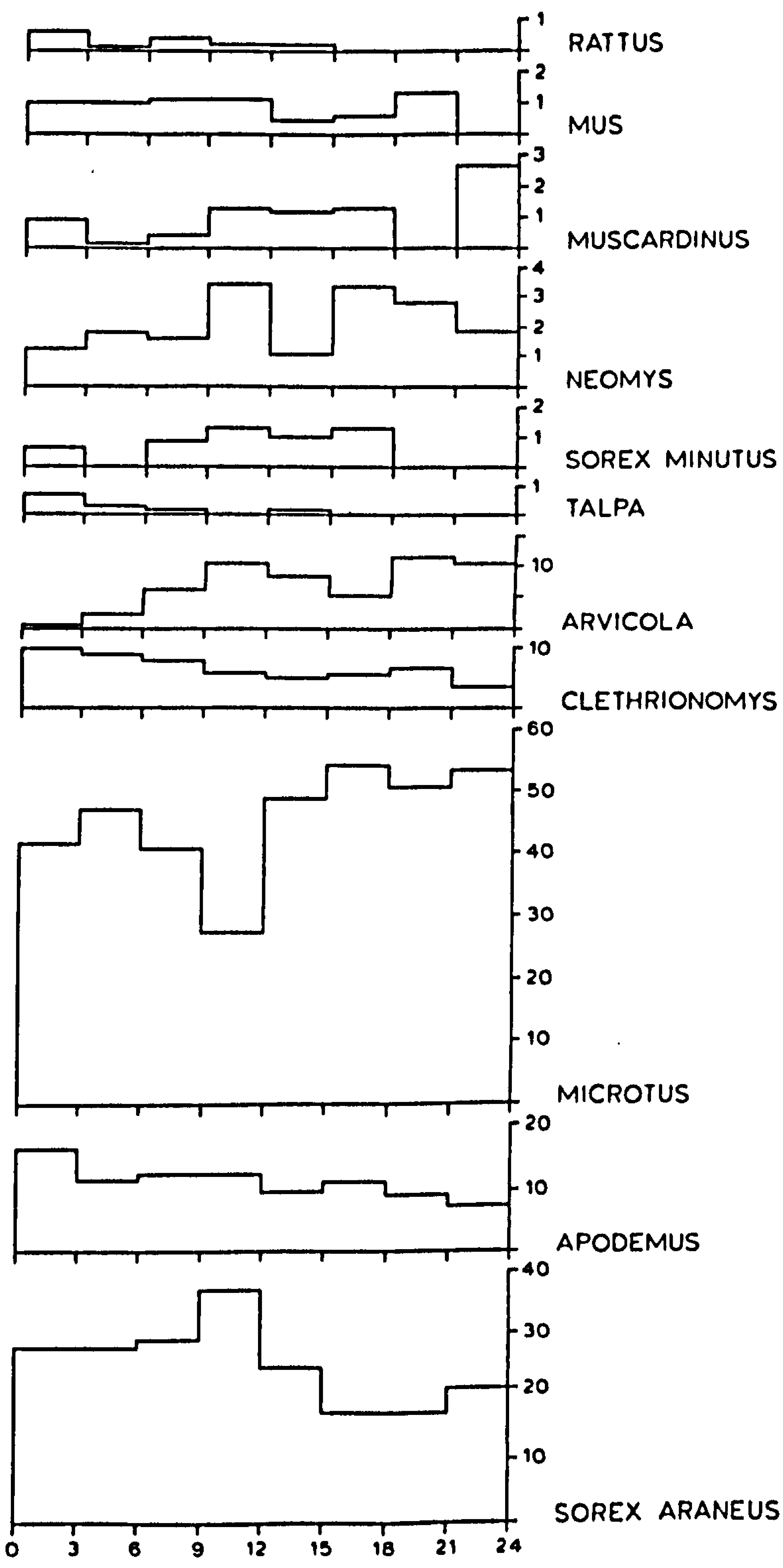
Problems of the Mendip Vertebrate Record

For the purpose of Quaternary studies the primary interest of the fossil vertebrate record is the use in revealing past environmental conditions. However, the factors that distort this palaeoenvironmental signal must be controlled if unbiased palaeoenvironmental reconstructions are required. The major factors affecting the Mendip's record are the effects of taphonomy and the quality of the excavations.

Taphonomy

The vast majority of Mendip region fossil vertebrate sites are cave entrance deposits. The primary agent of accumulation was predator activity. Therefore the species present cannot be considered a random selection of the species living at that time but will be biased by predator selection. Predators and natural weathering will also preferentially destroy the more fragile parts of skeletons, resulting in only the hardest bones surviving (particularly teeth). Although taphonomic processes introduce major biases into the record, research during the past 20 years has demonstrated the size and

FIGURE 5.4 : Percentage of small mammal fauna at varying depths at Ossoms Eyrie cave, Staffs. (Scales differ according to sample size.) (Brothwell & Jones 1978.)



nature of these effects. Since the work of Voorhies (1969) and Sutcliffe (1970) much of the fossil vertebrate material from UK cave sites has undergone taphonomic analysis, using techniques largely developed elsewhere (Brain 1974, 1980; Behrensmeyer 1978; Behrensmeyer *et al* 1979; Hill & Walker 1972; Mayhew 1977, Sutcliffe 1977, Wolff 1975). These studies were all carried out in tropical and sub-tropical environments. However, recently Andrews and Cooke (1985) have examined the taphonomic decay of a cow skeleton at Draycott in the Mendip region. The cow died from a fall into a cave entrance and its remains were studied over a 7½ year period. This represents the first such study in a temperate region.

Table 5.2 lists the primary taphonomic agents of bone accumulations from Mendip region cave sites based mainly upon analysis of fossil material preserved in museum collections. Although these results are the best available they should be treated with some caution since much of the material from sites excavated during the last century has not been preserved. However, taphonomic analysis does allow sites of broadly similar natures to be compared. If two Hyaena den accumulations with similar preservations but of different ages are compared, then any faunal differences are more likely to be due to changes in the composition of prey species than to taphonomic biases. Conversely, if natural trap sites and Hyaena dens of the same ages are compared, then faunal differences are likely to be due to taphonomic biases rather than to environmental differences. This will only be true if the sample sizes of the excavated deposits are sufficiently large, since it is known that small samples can significantly bias the results of mammalian fossil studies (Grayson 1981; Wolff 1975).

The Quality of Excavations

Most Mendip fossil vertebrate sites were excavated during the last century before the importance of stratigraphy was fully realised. Excavations were typically done by 'workmen' employed by the

TABLE 5.2 : PRIMARY TAPHONOMIC MECHANISM OF FOSSIL BONE ACCUMULATIONS FROM SELECTED MENDIP REGION CAVES

Cave Site	Mechanism of Accumulation	Source
Banwell Bone Cave	Natural Trap	Hunt 1955
		Sutcliffe 1955
Durdham Down	"	Turner 1982
Hutton Cave	"	Turner 1981
Sandford Hill	"	Boyle 1983
Hyaena Den, Wookey.	Hyaena Dens	Campbell 1977
Milton Hill	"	Boyle 1983
Picken's Hole	"	Turner 1981
Uphill Cave	"	Boyle 1983
Walton (Clevedon) Cave	Wolf Den	"
Bleadon Cave	Lion Den	"
Westbury-Sub-Mendip:		
Layer 1	Fluvial Deposition	Bishop 1982
Layers 3-9	Bear Den	"
Layer 10(Rodent Earth)	Owl Pellets	"
Gough's Cave	Human Butchers	Parkin *et al* 1986

'scientist', who, like Boyd Dawkins, would occasionally sit outside the cave and *"personally examine every wheelbarrow of cave earth"* (Sutcliffe 1957; Bishop 1983). This methodology meant that not only was the resulting fossil assemblage unrelated to any stratigraphy but that the larger and more easily identifiable bones were preferentially collected in comparison to smaller bones and bone fragments. Small fossil mammals such as rodent remains were often not collected at all (Sutcliffe & Kowalski 1976). By the early 20th Century careful excavators such as Parry dug in '6" spits' and recorded the depth at which fossil material was recovered. However, even these scientists rarely related the spit depths to changes in stratigraphy, although there are notable exceptions such as the Aveline's Hole (Davies 1925) and Soldiers Hole (Parry 1931) excavations.

Another problem with the Mendip fossil vertebrate record is that much of the original material has been lost or destroyed. The more spectacular fossils were often not donated to museums but sold or given as trophies to local dignitaries. Occasionally museum material was poorly curated and fossils from several different sites have become inter-mixed (Turner 1981); and fossil material from a number of Mendip sites was destroyed when the UBSS and Royal College of Surgeons museums were bombed during the war (C Hawkes *per com*).

This loss of material means that it is impossible to revise many of the faunal lists from Mendip sites by separating mixed age material by preservation state, or to re-identify fossil remains in the light of taxonomic revisions. The quality of many original vertebrate identifications was often very poor (A Currant *per com*).

Mendip fossil vertebrate records are typically contaminated by faunas of different ages, biased towards the larger species, and prone to containing misidentified specimens. Therefore any attempts at analysing this record must employ 'robust' techniques that are insensitive to 'outliers' and 'noise'.

CHAPTER VI

STATISTICAL ANALYSIS OF THE FOSSIL VERTEBRATE DATA FROM THE MENDIP REGION

Introduction

As discussed in Chapter V the main interest of Quaternary studies in fossil vertebrate data is their potential for palaeoenvironmental reconstruction. However, this potential is limited by biases in this record. Therefore statistical analysis is appropriate if it can help deconvolute the true palaeoenvironmental signal from the 'noise'. In the absence of absolute or relative dates on fossil vertebrate sites, correlation of sites of similar ages must be undertaken on the basis of the fossil vertebrates present in order to construct a biostratigraphy. These correlations have in the past been undertaken by 'experts' on the basis of their 'years of experience' and usually rely on the presence of certain key 'indicator' fossils such as *Hippopotamus amphibius* (Hippo) which has been taken as indicative of an Ipswichian age (Stuart 1982).

This subjective approach can be criticised on a number of bases:

1) It ignores the majority of the fauna present and therefore can lead to whole faunas being incorrectly dated if they are contaminated by just a few indicator species.

2) The 'experts' often disagree about the value of species as indicators and the resultant biostratigraphy that this yields, eg the debate between Sutcliffe (1985) and Stuart (1982) or the debate between Turner (1981) and Stringer & Currant (1981).

3) There is a great danger of tautological argument, ie if Hippo is taken as an indicator fossil of an 'Ipswichian' age, then all sites containing Hippo will be classified as 'Ipswichian'. However, as discussed previously (Chapters II, III, IV), the speleothem record shows that there were not one but three warm periods during the 'last interglacial' (Ipswichian). Hippo may well have been present during all or only some of these warm periods.

For these reasons the application of numerical taxonomic methods to the Mendip vertebrate record is useful, since these methods will potentially classify the faunal record on the basis of the total fauna, as well as indicate the most useful indicator species. These groupings are no more 'scientific' than the 'experts' informal 'indicator' species classification. However they have the advantage that the assumptions used to classify the faunal record are explicit.

The non-quantitative methods of sampling used by 19th century investigators and the subsequent loss of much of this original fossil material renders impossible any statistical analysis of the relative proportions of different species present at these sites. However the records of the presence or absence of mammal species is relatively more reliable, with the proviso that the misidentification of species and contamination due to the lack of stratigraphic control has probably resulted in between 0 to 20% of the presence or absence data being incorrect. Therefore, any statistical analysis that includes sites excavated during the 19th century must be:

1) applicable to categorical data (presence/absence);

2) robust enough to produce reliable answers with data sets containing approximately 20% noise.

The group of techniques that comes closest to fulfilling these criteria is hierarchical cluster analysis, particularly Ward's method which is known to yield reliable solutions even where a considerable degree of cluster overlap is present (Hands & Everitt 1987 - see Appendix 3 for details).

Problems and Potential of Clustering the Mendip Region Vertebrate Record

As discussed previously, the most significant problems with the Mendip region vertebrate record are those of contamination and misidentification which induce 'noise' into the record. Although cluster analysis has been demonstrated to be a robust technique with data sets from many disciplines, it is necessary to test its utility when applied to typical Mendip faunal data, in order to determine the nature and validity of the solutions produced.

Gough's Cave Faunal Record

The faunal record from Gough's Cave is typical of that from many Mendip sties. The animal remains are known largely from the work of Parry (1929,1931) who excavated the entrance deposits between 1927 to 1931. He dug the deposits in six inch (≈15cm) spits but took no account of any lateral variation in the trend of bedding. The resulting faunal record is therefore 'noisy' with material from one 'layer' being intermixed with material from other 'layers', particularly where they dipped near the cave walls. Much of the faunal material recovered between 1927 to 1931 has been lost and the surviving material *"bears all the hallmarks of fairly drastic selection with a strong bias towards easily identifiable specimens"* (Currant 1986). Recently Currant (1986) has re-examined the faunal material and re-identified all surviving specimens. The faunal list has been revised in the light of modern taxonomic nomenclature and is shown in Figure 6.1. Extensive work has also been undertaken on radiocarbon dating vertebrate remains from Gough's cave. 25 dates are now available and further work is being undertaken (Burleigh 1986). Using the dating results, Currant (1986) has identified two

FIGURE 6.1 : Gough's Cave fossil mammal data as divided by Parry's (1931) excavation spits and on the basis of ^{14}C dating (Currant 1986).

. . — *The spit distribution of Pleistocene mammal remains from Parry's 1927-1931 excavations*

spits	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*
Ochotona pusilla						1													
Lepus timidus		2	1	2	5	7	6	3	9	2		1							
Castor fiber					1				1										
Lemmus lemmus						1													
Arvicola terrestris						*	1	1											
Canis lupus			1	1				1	3	2	1	*							
Alopex lagopus						1			*										
Vulpes vulpes	*	1	1		*	3	1			1		1	5						
Ursus arctos				3		*	2	*	3										
Equus ferus	*		10	6	15	25	11	27	63	21	15	12	5	3	4	*	*	*	1
Cervus elaphus	*	*				8	6	8	8	3	1	1	2						
Rangifer tarandus		*	1		3	2			*										
Bos primigenius		*		*	*	2	1			1									
Saiga tatarica									1	1									

Figures indicate the numbers of individual specimens with original excavation data in the British Museum (Natural History) collections.
Asterisks denote material mentioned in published reports but no longer traceable in surviving collections.

. . . — *Stratigraphic subdivision of the Lateglacial Period.*

Radiocarbon years bp	*Climatostratigraphic units*	*Gough's Cave*
	Flandrian Interglacial	Cheddar Man
10,000		
	transition	reindeer
10,500		
	Younger Dryas Stadial	
11,000		
	transition	
12,000		
	Lateglacial Interstadial	human occupation. horse, red deer, arctic hare fauna
13,000		
	transition	
14,000		
	Late Devensian Main Stadial	

distinct faunas at Gough's cave, a late glacial interstadial fauna to which the majority of the vertebrate remains belong, and an impoverished late glacial stadial fauna comprising Reindeer and possibly a few other hardy species (Figure 6.1). However the presence of two distinct faunas is far from clear in the species list (Figure 6.1). Cluster analysis was undertaken on the Gough's cave fauna sub-divided by spit numbers (Figures 6.2,6.3). The results from both Ward's and the centeroid method clearly show that two clusters are present. The cluster diagnostic statistics demonstrate that the two cluster solutions are optimum and statistically valid at better than the 1% level (Table 6.1). The cophenetic correlation and delta statistic values also indicate that the hierarchical solution adequately represent the initial data without too much distortion (see Appendix 3).

Although the optimum position of spit 15 differs between the two solutions, the species composition of the resulting clusters is similar (Table 6.2). As would be expected with contaminated data the overall percentage occurrence between the two clusters is also similar. However the binary frequency ratio results show the distinct species differences between the two clusters. The two resulting faunas (Table 6.2) are effectively identical to those proposed by Currant (1986) on the basis of radiocarbon dates (Figure 6.1).

The majority of the fauna (Cluster 2) is probably all of 'Windermere' interstadial age, while the impoverished Loch Lomond stadial fauna is comprised of just Reindeer and Red Fox. The anomalous presence of Beaver in Cluster 1 of the centeroid method is interesting. It may indicate the presence of a third early Holocene fauna at Gough's cave which could correspond with the early Holocene hominid remains found there (Cheddar Man), or alternatively it may be incorrectly clustered.

It is clear from the Gough's cave analysis that hierarchical cluster analysis yields correct solutions with presence/absence faunal data

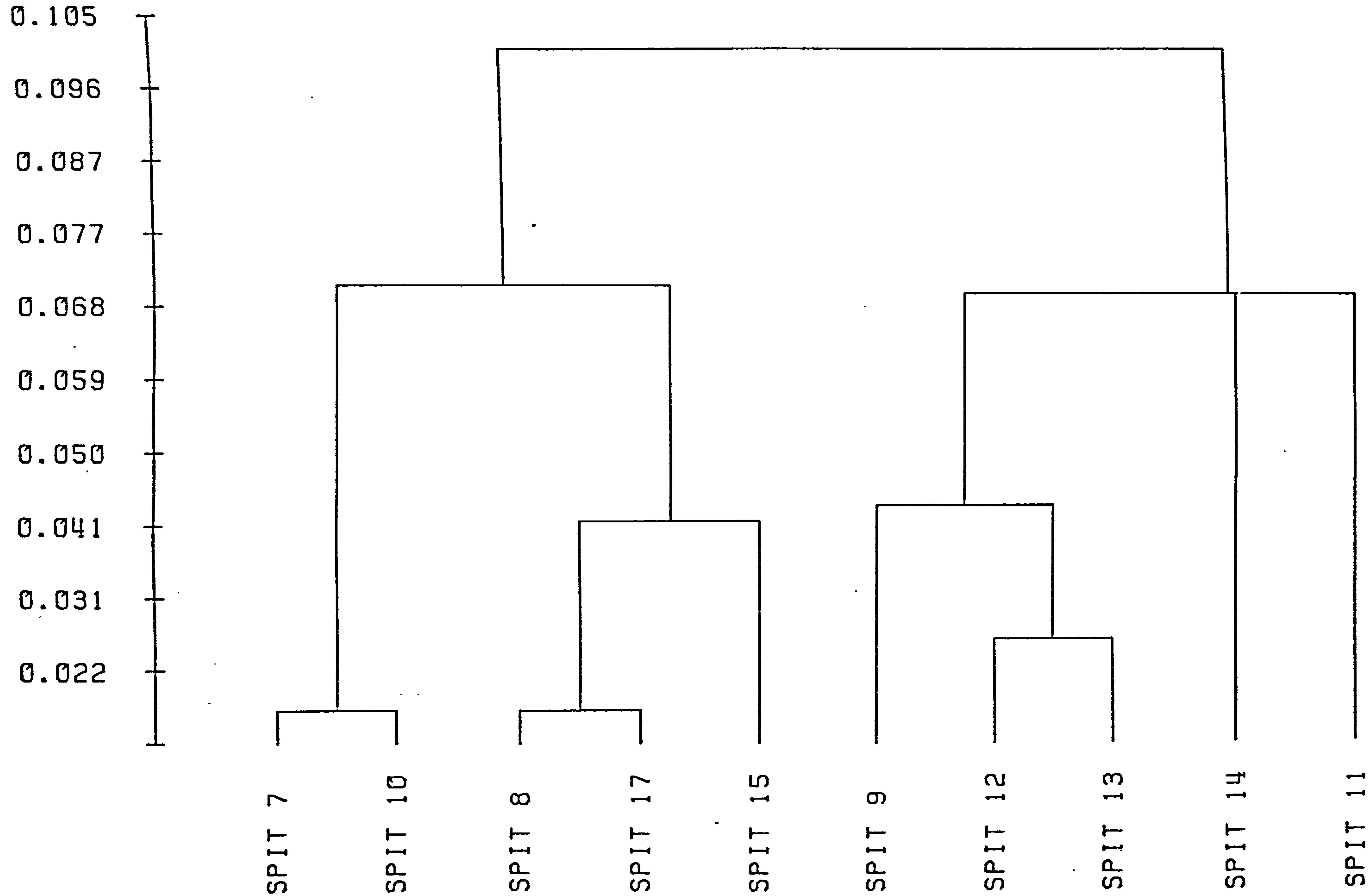


FIGURE 6.2 : GOUGHS CAVE MAMMAL DATA. WARDS METHOD USING EUCLIDEAN DISTANCE.

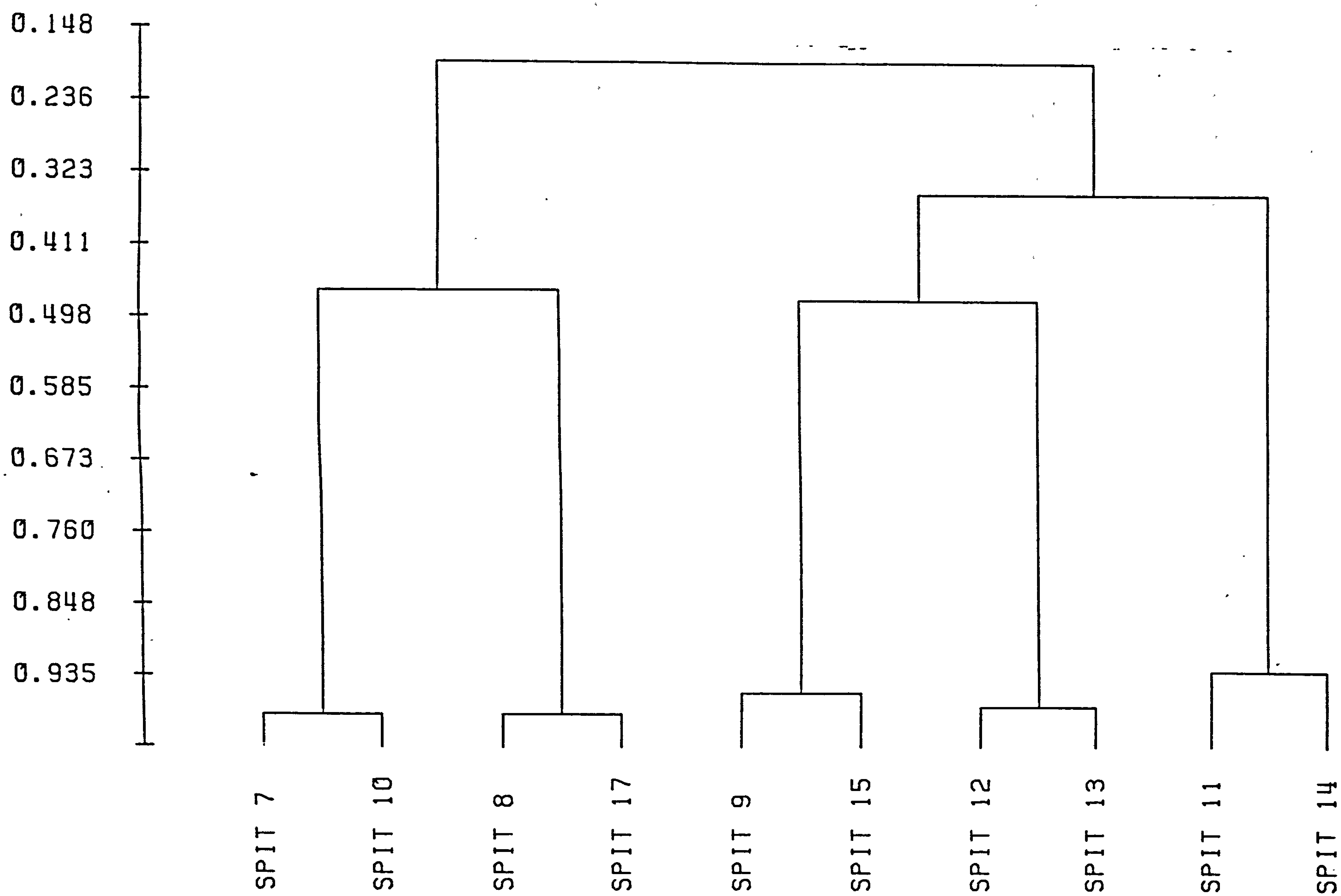


FIGURE 6.3 : GOUGHS CAVE MAMMAL DATA. CENTROID METHOD USING SIMPLE MATCHING.

TABLE 6.1 : CLUSTER DIAGNOSTIC STATISTICS FOR THE GOUGH'S CAVE MAMMAL DATA

Mean = 0,05 Standard deviation = 0,03

Mean = 0,7 Standard deviation = 0,33

Ward's Method			Centeroid Method		
Predicted clusters	Realised deviates	T values (7 d.of f.)	Predicted clusters	Realised deviates	T values (7 d.of f.)
2	1,74	4,92	2	-1,58	4,46
3	0,70	1,98	3	-1,09	3,08
5	0,67	1,84	4	-0,73	2,06
4	0,67	1,84	5	-0,69	1,95

Cophenetic correlation = 0,55
Delta 0 = 0,85
Delta 1 = 0,71
Delta 2 = 0,62

Cophenetic correlation = 0,42
Delta 0 = 0,80
Delta 1 = 0,67
Delta 2 = 0,63

TABLE 6.2 : GOUGH'S CAVE CLUSTER ANALYSIS RESULTS

WARD'S METHOD RESULTS

Cluster 1 = Spits 7,8,10,15,17 | Cluster 2 = Spits 9,11,12,13,14

Species	% Occurrence	Species	BFR	Species	% Occurrence	Species	BFR
Red Fox	100	Red Fox	1,43	Brown Bear	100	Arctic Fox	2,00
Mountain Hare	100	Reindeer	1,43	Mountain Hare	100	Brown Bear	2,00
Horse	80			Man	100	Water Vole	2,00
Aurochs	60			Red Deer	80	Norway Lemming	2,00
Wolf	60			Horse	60	Steppe Pika	2,00
Reindeer	60			Aurochs	60	Red Deer	1,33
Man	60			Wolf	60	Man	1,25
				Water Vole	60		

CENTROID METHOD RESULTS

Cluster 1 = Spits 7,8,10,17 | Cluster 2 = Spits 9,11,12,13,14,15

Species	% Occurrence	Species	BFR	Species	% Occurrence	Species	BFR
Red Fox	100	Reindeer	1,50	Man	100	Arctic Fox	1,67
Mountain Hare	100	Red Fox	1,43	Mountain Hare	100	Sagia	1,67
Horse	75	Beaver	1,25	Red Deer	83	Mountain Hare	1,67
Reindeer	75			Horse	83	Water Vole	1,67
Wolf	50			Brown Bear	83	Norway Lemming	1,67
Aurochs	50			Wolf	67	Brown Bear	1,67
Man	50			Aurochs	67	Red Deer	1,39
				Red Fox	50	Man	1,25
				Water Vole	50	Aurochs	1,11
						Wolf	1,11
						Horse	1,04

even if contamination is present. Ward's method tends to yield statistically more significant solutions than the centeroid method at the expense of slightly increased distortion in relation to the initial similarity matrix.

Westbury-sub-Mendip Faunal Record

The Westbury-sub-Mendip fauna was clustered to show the effects of taphonomy on cluster solutions (see Chapter V). The fauna has been sub-divided by the beds described by Bishop (1982), who recognised 3 faunas:

1) an impoverished lower Pleistocene fauna composed of the relatively few species from Bed 1;

2) a mid Pleistocene fauna resulting from a bear den accumulation found in Beds 2 to 9;

3) a mid Pleistocene rodent fauna resulting from owl pellet accumulations (Wilson 1980, Bishop 1982) found in Bed 10, but of similar age to the bear den fauna.

These three divisions are also sedimentologically distinct (see Chapter 1X).

The Ward's method cluster analysis solution (Figure 6.4) shows that Bed 10 has clustered out separately with Bed 5, which is part of Bishop's bear den fauna. However Bed 5 contains a rich fauna with a large number of rodents in comparison with Beds 3 to 8. The association of Beds 5 and 10 is therefore unsurprising. The Bed 1 fauna has also clustered out separately as would be expected. The cluster diagnostic statistics indicated that both the 2 and 3 cluster

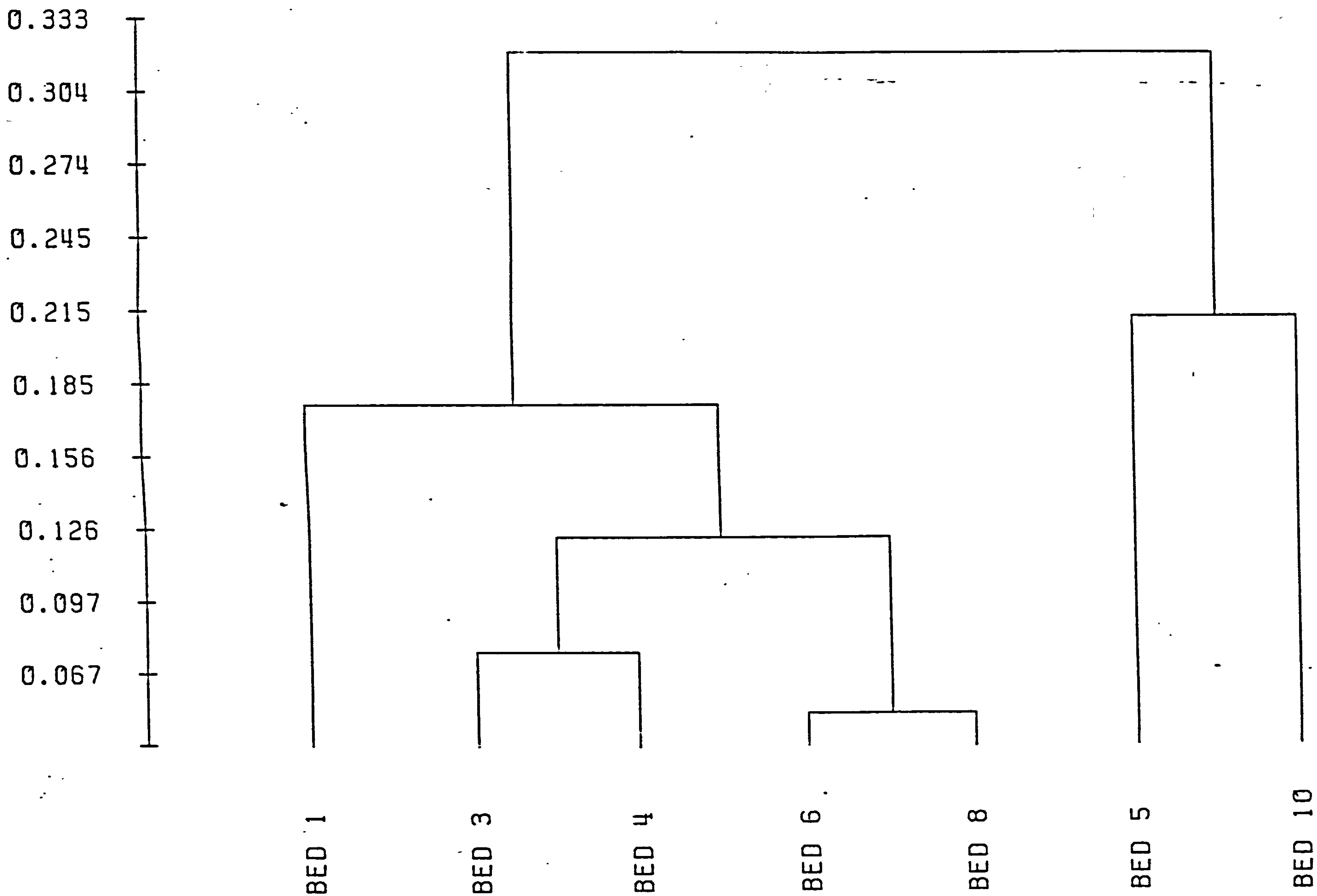


FIGURE 6.4 : Dendrogram of Westbury-sub-Mendip mammal data clustered by Ward's method from a Euclidean distance matrix.

TABLE 6.3 : CLUSTER DIAGNOSTIC STATISTICS FOR WESTBURY-SUB-MENDIP FAUNAL DATA (WARD'S METHOD USING EUCLIDEAN DISTANCE)

Mean = 0.16 Standard deviation = 0.09

Predicted clusters	Realised deviates	T-values (5 d of f)
2	1.62	3.97
3	0.53	1.30
4	0.17	0.42

Cophenetic correlation = 0.81
Delta 0 = 0.71
Delta 1 = 0.51
Delta 2 = 0.41

solutions are significant at better than the 1% level and that little similarity matrix distortion is caused by the solution. (Table 6.3)It is clear from the Westbury-sub-Mendip cluster analysis that, as expected, taphonomic factors can have an equal influence upon the results, as do temporal factors (see Chapter V). This presents a problem with clustering the Mendip region faunal data since it includes faunas from both 'open' and 'cave' sites. The number of sites is insufficient to cluster these two groups of faunas separately. However,if they are clustered together it can be expected that taphonomic factors may affect the solution as significantly as temporal factors. Therefore, in order to interpret the cluster solutions for the Mendip region faunas, it is first necessary to look at the UK 'cave' and 'open' site Pleistocene faunas in order to control for this taphonomic effect and to place the Mendip region record into a wider context.

42 mammal faunas from 38 UK Quaternary 'open' sites and 36 mammal faunas from 21 UK Quaternary 'cave' sites, excluding the Mendip region, were available for analysis. The data are listed in Appendix 2 along with the 42 mammal faunas from 38 Mendip region sites. The UK data are by no means complete but represents some of the most reliable data available. The percentage occurrence of the most commonly occurring mammal species in the three data sets is shown in Table 6.4. As would be expected (Chapter V) the cave site faunas contain a greater percentage of carnivore and rodent species, reflecting the superior preservation of cave faunas compared to open country faunas, which are often recovered from gravel terraces or other water lain deposits. The Mendip region data fall between these two extremes but closer to the UK 'cave' data resulting from the number of cave faunas compared with the open country faunas present.

<u>The UK 'Open' Site Cluster Analysis</u>

The dendrogram of the cluster solution of Ward's method using the euclidean distance similarity matrix calculated from the UK 'open'

TABLE 6.4 : COMPARISON OF THE PERCENTAGE OCCURRENCE OF MAMMALIAN SPECIES IN UK FAUNAL SITES (Only those species occurring in more than 25% of the faunas are shown)

UK Open Sites, Total Number of Faunas = 42

LARGE HERBIVORES		LARGE CARNIVORES		SMALL MAMMALS	
Horse	57	Wolf	29	Extinct Water Vole (*Arvicola cantiana*)	33
Bison	50	Spotted Hyaena	26	Bank Vole	29
Red Deer	48	Man	26		
Mammoth	33				
Straight-Tusked Elephant	31				
Aurochs	26				
Giant Deer	26				
Woolly Rhino	26				
Steppe Rhino	26				

UK Cave Sites, Total Number of Faunas = 36

LARGE HERBIVORES		LARGE CARNIVORES		SMALL MAMMALS	
Bison	44	Red Fox	58	Water Vole	40
Red Deer	42	Wolf	56	Field Vole	33
Horse	33	Brown Bear	53	Northern Vole	33
Reindeer	31	Spotted Hyaena	39	Wood Mouse	28
Aurochs	31	Lion	33	Bank Vole	25
Steppe Rhino	28	Badger	28	Arctic Lemming	25
		Lynx	25		

Mendip Region Sites, Total Number of Faunas = 44

LARGE HERBIVORES		LARGE CARNIVORES		SMALL MAMMALS	
Horse	59	Red Fox	50	Mountain Hare	36
Red Deer	54	Wolf	48	Tundra Vole	32
Reindeer	54	Brown Bear	47	Northern Vole	30
Bison	48	Lion	30	Water Vole	30
Aurochs	36	Spotted Hyaena	27	Arctic Lemming	30
Wild Boar	34			Norway Lemming	27
Mammoth	34			Common Vole	25
Giant Deer	25				

site data shows a complex structure (Figure 6.5). There is no obvious optimum number of clusters and the realised deviates generated using Stopping Rule 1 (Mojena 1977) decrease linearly from the 2 cluster to 11 cluster solution, confirming the presence of no optimum solution. The cluster diagnostic statistics shown in Table 6.5 show the maximum values for the realised deviates generated by Rule 1 or 2 (see Appendix 3). The distortion statistics indicate some degree of divergence of the hierarchical solution from the similarity matrix but this is relatively small considering the number of faunas clustered.

At least 13 distinct clusters are present, the characteristic faunas of which are listed in Table 6.6. Clusters 1 and 2 are clearly lower Pleistocene in age, the Cluster 1 fauna from the Red Crag is considered to be Pliocene/Pleistocene in age (Spencer 1966). The Cluster 2 faunas all derive from the Icenian Crag (Norwich and Weybourne Crags) which has a complex and poorly understood stratigraphy, but is known to span several interglacial/glacial cycles (Beck *et al* 1972, Norton 1977).

Mayhew (1985) has proposed that these Icenian Crag faunas can be subdivided into 3 groups on the basis of their rodent faunas:

1) Faunal Type A - a pre-Pastonian/Pastonian fauna found at several sites. including West Runton (Crag) and East Runton (Crag) sites.

2) Faunal Type B - a pre-Baventian fauna found at several sites, including East Bavents (the Baventian type site).

3) Faunal Type C - a Bramertonian fauna found at sites, including Blake's Pit (Bramertonian type site) and Thorpe/Norwich.

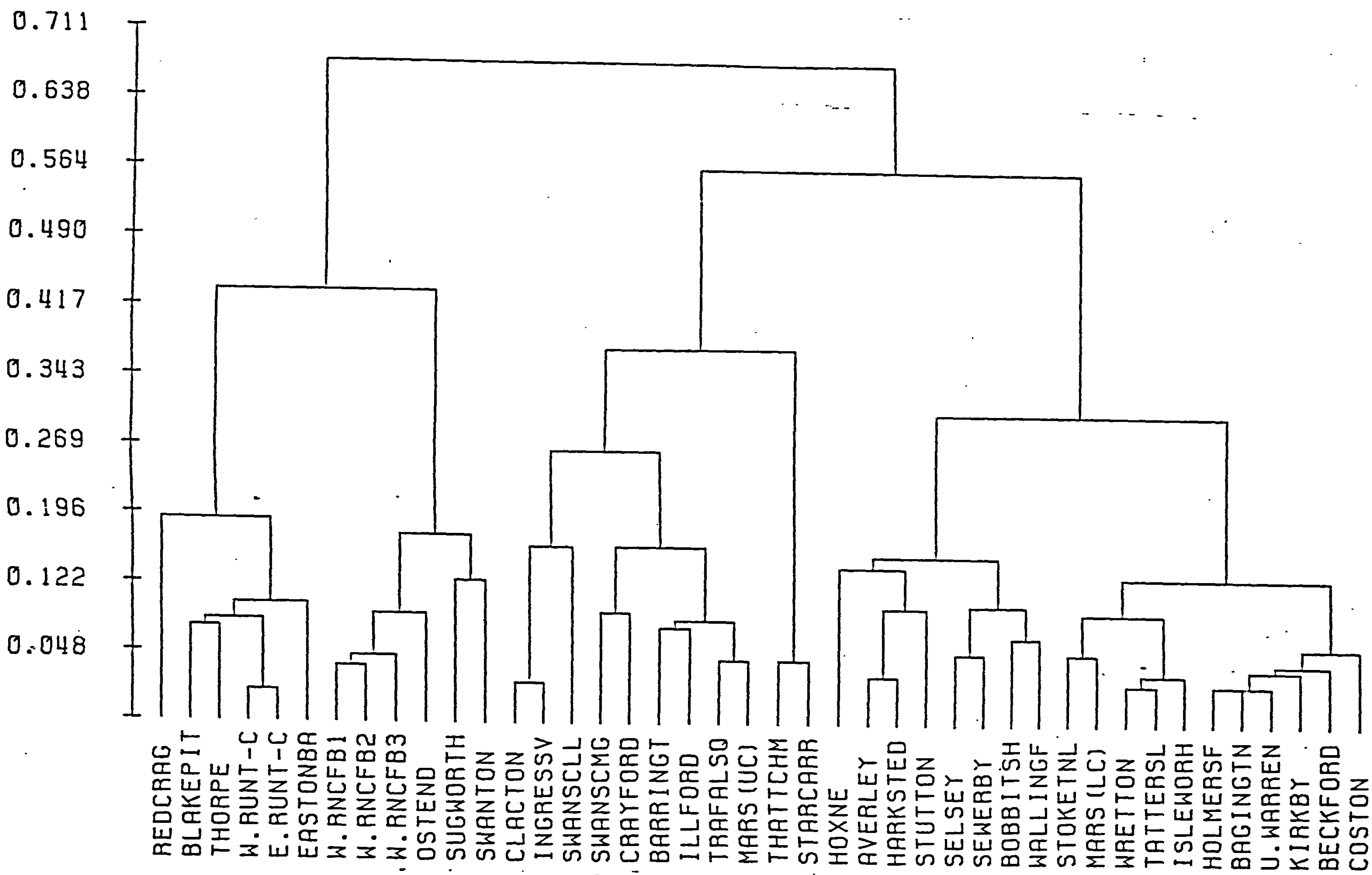


FIGURE 6.5 : Dendrogram of UK 'open' site mammal data clustered by Ward's method from a Euclidean distance matrix.

TABLE 6.5 : CLUSTER DIAGNOSTIC STATISTICS FOR WARD'S SOLUTION TO UK 'OPEN' SITE DATA

Mean = 0,130
Standard Deviation = 0,148

PREDICTED CLUSTERS	REALISED DEVIATES	t-VALUE (39 Degrees of Freedom)
2	3,71	23,2
3	3,07	19,2
4	2,46	15,4
5	2,46	15,4
6	2,08	13,0
7	2,20	13,7
8	0,69	4,3
9	0,30	1,9
10	0,21	1,3
11	0,61	3,8
12	0,68	4,2
13	0,69	4,3
15	0,67	4,2
25	0,73	4,6

Cophenetic Correlation = 0,57
Delta 0 = 2,17
Delta 1 = 2,97
Delta 2 = 2,84

TABLE 6.6 : UK 'OPEN' SITES CLUSTER ANALYSIS RESULTS

CLUSTER 1. NUMBER OF FAUNAS = 1. SITE: Red Crag.

Species Common Name	Species Latin Name	% Occurrence	Species Common Name	Species Latin Name	Binary Frequency Ratio
Mountain Hare	*Lepus timidus*	100	Extinct Deer	*Eucladoceros tetraceros*	42
Beaver	*Castor fiber*	100	Walrus	*Trichechus huxleyi*	42
Wolf	*Canis lupus*	100	Gomphothere Mastodont	*Anancus arvernensis*	21
Red Fox	*Vulpes vulpes*	100	Extinct Deer	*Eucladoceros tetraceros*	21
Walrus	*Trichechus huxleyi*	100	Whale, Dolphin or Porpoise sp.	*Cetacea sp.*	21
Extinct Elephant	*Archidiskodon meridionalis*	100	Mountain Hare	*Lepus timidus*	21
Gomphothere Mastodont	*Anancus arvernensis*	100	Extinct Horse	*Equus stenonis*	21
Extinct Callabine Horse	*Equus caballus sp*	100	Extinct Callabine Horse	*Equus caballus sp.*	14
Extinct Horse	*Equus stenonis*	100	Red Fox	*Vulpes vulpes*	14
Giant Deer	*Megaceros verticornis*	100	Extinct Deer	*Eucladoceros sedgwicki*	14
Extinct Deer	*Eucladoceros falconeri*	100	Extinct Deer	*Eucladoceros falconeri*	14
Extinct Deer	*Eucladoceros sedgwicki*	100	Giant Deer	*Megaceros verticornis*	14
Extinct Deer	*Eucladoceros tetraceros*	100	Extinct Elephant	*Archidiskodon meridionalis*	10.5
Extinct Gazelle	*Gazella angelica*	100	Beaver	*Castor fiber*	4.7
Whale, Dolphin, Porpoise sp.	*Cetacea sp.*	100	Wolf	*Canis lupus*	3.5

CLUSTER 2. NUMBER OF FAUNAS = 5.
SITES: Blakes Pit (Lower Shell Bed), Thorpe/Norwich, Easton Bavents, West Runton (Crag), East Runton (Crag).

Species Common Name	Species Latin Name	% Occurrence	Species Common Name	Species Latin Name	Binary Frequency Ratio
Extinct Vole	*Mimomys pliocaenicus*	100	Extinct Vole	*Mimomys pliocaenicus*	8.4
Extinct Vole	*Mimomys reidi*	100	Extinct Vole	*Mimomys rex*	8.4
Extinct Vole	*Mimomys newtoni*	80	Extinct Vole	*Mimomys reidi*	8.4
Extinct Elephant	*Archidiskodon meridionalis*	60	Extinct Vole	*Mimomys newtoni*	8.4
Extinct Vole	*Mimomys blanci*	60	Extinct Vole	*Mimomys altenburgensis*	8.4
Extinct Deer	*Eucladoceros falconeri*	40	Extinct Vole	*Mimomys pitymyoides*	8.4
Extinct Deer	*Eucladoceros sedgwicki*	40	Extinct Vole	*Mimomys blanci*	8.4
Extinct Vole	*Mimomys altenburgensis*	40	Extinct Otter	*Aonyx sp.*	8.4
Extinct Vole	*Mimomys pitymyoides*	40	Seal	*Phoca sp.*	8.4
			Extinct Hippo	*Hippopotamus major*	8.4
			Extinct Elephant	*Archidiskodon meridionalis*	6.3
			Extinct Deer	*Eucladoceros falconeri*	5.6
			Extinct Deer	*Eucladoceros sedgwicki*	5.6
			Gomphothere Mastodont	*Anancus arvernensis*	4.2
			Extinct Horse	*Equus stenonis*	4.2
			Extinct Gazelle	*Gazella angella*	4.2
			Whale, Dolphin or Porpoise sp.	*Cetacea sp.*	4.2
			Giant Deer	*Megaceros verticornis*	2.8

Species Common Name	Species Latin Name	% Occurrence	Species Common Name	Species Latin Name	Binary Frequency Ratio
CLUSTER 3. NUMBER OF FAUNAS = 4. SITES: West Runton (Faunas B1-3), Ostend.					
Common Vole	*Microtus arvalis*	100	Extinct Shrew	*Sorex runtonensis*	10.5
Extinct Shrew	*Sorex savini*	100	Extinct Water Shrew	*Neomys newtoni*	10.5
Bank Vole	*Clethrionomys glareolus*	100	Extinct Squirrel	*Sciurus whitei*	10.5
Extinct Shrew	*Sorex runtonensis*	75	Weasel	*Mustela nivalis*	10.5
Mole	*Talpa europaea*	75	Extinct Elephant	*Mammuthus trogontherii*	10.5
Russian Desman	*Desmana moschata*	75	Extinct Shrew	*Sorex savini*	8.4
Wood Mouse	*Apodemus sylvaticus*	50	Mole	*Talpa europaea*	7.9
			Russian Desman	*Desmana moschata*	7.9
			Common Vole	*Microtus arvalis*	5.2
			Extinct Callabine Horse sp.	*Equus caballus sp.*	5.2
			Bank Vole	*Clethrionomys glareolus*	3.5
			Wood Mouse	*Apodemus sylvaticus*	3.5
			Roe Deer	*Capreolus capreolus*	3.0
			Extinct Beaver	*Trogontherium cuvieri*	2.1
CLUSTER 4 ? NUMBER OF FAUNAS = 2. SITES: Sugworth, Swanton Morley.					
Pigmy Shrew	*Sorex minutus*	100	Pigmy Shrew	*Sorex minutus*	21
Bank Vole	*Clethrionomys glareolus*	100	Extinct Shrew	*Beremendia cf. fissidens*	21
Wood Mouse	*Apodemus sylvaticus*	100	Extinct Vole	*Pliomys episcopalis*	21
Red Deer	*Cervus Elaphus*	100	Extinct Water Vole	*Mimomys savini*	21
			Extinct Bison	*Bison schoetensacki*	21
			Extinct Mole	*Talpa minor*	10.5
			Wood Mouse	*Apodemus sylvaticus*	6.0
			Common Shrew	*Sorex araneus*	5.25
			Extinct Shrew	*Sorex savini*	5.25
			Bank Vole	*Clethrionomys glareolus*	5.25
			Spotted Hyaena	*Crocuta crocuta*	5.25
			Hippopotamus	*Hippopotamus amphibius*	5.25
CLUSTER 5. NUMBER OF FAUNAS = 3. SITES: Clacton, Swanscombe (Lower Loam & Gravel), Ingress Vale.					
Wood Mouse	*Apodemus sylvaticus*	100	Extinct Pine Vole	*Pitymys arvaloides*	14
Man	*Homo sapiens*	100	Deningeri's/Cave Bear	*Ursus deningeri/spelaeus*	14
Lion	*Panthera leo*	100	Extinct Rhino	*Dicerorhinus kirchbergensis*	14
Straight Tusked Elephant	*Palaeoloxodon antiquus*	100	Wild Boar	*Sus scrofa*	8.4
Horse	*Equus ferus*	100	Extinct Mole	*Talpa minor*	7.0
Extinct Rhino	*Dicerorhinus kirchbergensis*	100	Macaque Monkey	*Macaca sp.*	7.0
Steppe Rhino	*Dicerorhinus hemitoechus*	100	Rabbit	*Oryctolagus cuniculus*	7.0
Wild Boar	*Sus scrofa*	100	Extinct Beaver	*Trogontherium cuvieri*	5.6
Red Deer	*Cervus elaphus*	100	Fallow Deer	*Dama dama*	5.25
Fallow Deer	*Dama dama*	100	Pine Martin	*Martes martes*	4.7
Aurochs	*Bos primigenius*	100	Wild Car	*Felis sylvestris*	4.7
Extinct Beaver	*Trogontherium cuvieri*	67	Man	*Homo sapiens*	3.8
Bank Vole	*Clethrionomys glareolus*	67	Lion	*Panthera leo*	3.8
Common Vole	*Microtus avarlis*	67	Steppe Rhino	*Dicerorhinus hemitoechus*	3.8
			Aurochs	*Bos primigenius*	3.8

Species Common Name	Species Latin Name	% Occurrence	Species Common Name	Species Latin Name	Binary Frequency Ratio
CLUSTER 6. NUMBER OF FAUNAS = 2. SITES: Swanscombe (Upper Middle Gravel), Crayford.					
Man	*Homo sapiens*	100	Susliks	*Spermophilus sp.*	24
Norway Lemming	*Lemmus lemmus*	100	Mountain Hare	*Lepus timidus*	10,5
Northern Vole	*Microtus oeconomus*	100	Arctic Lemming	*Dicrostonyx torquatus*	10,5
Wolf	*Canis lupus*	100	Norway Lemming	*Lemmus lemmus*	10,5
Lion	*Panthera leo*	100	Musk Ox	*Ouibos moschatus*	10,5
Horse	*Equus ferus*	100	Northern Vole	*Microtus oeconomus*	4,7
Steppe rhino	*Dicerorhinus hemitoechus*	100	Man	*Homo sapiens*	3,8
Red Deer	*Cervus elaphus*	100	Lion	*Panthera leo*	3,8
Giant Deer	*Megaceros giganteus*	100	Steppe Rhino	*Dicerorhinus hemitoechus*	3,8
Aurochs	*Bos primigenius*	100	Giant Deer	*Megaceros giganteus*	3,8
			Aurochs	*Bos primigenius*	3,8
CLUSTER 7. NUMBER OF FAUNAS = 4. SITES: Barrington, Trafalgar Square, Ilford, Marsworth (Upper Channel).					
Steppe Rhino	*Dicerorhinus hemitoechus*	100	Hippopotamus	*Hippopotamus amphibius*	7,9
Red Deer	*Cervus elaphus*	100	Steppe Rhino	*Dicerorhinus hemitoechus*	3,8
Giant Deer	*Megaceros giganteus*	100	Giant Deer	*Megaceros giganteus*	3,8
Bison	*Bison priscus*	100	Water Vole	*Arvicola terrestris*	3,5
Lion	*Panthera leo*	75	Badger	*Meles meles*	3,5
Straight Tusked Elephant	*Palaeoloxodon antiquus*	75	Lion	*Panthera leo*	2,9
Hippo	*Hippopotamus amphibius*	75	Aurochs	*Bos primigenius*	2,9
Aurochs	*Bos primigenius*	75	Spotted Hyaena	*Crocuta crocuta*	2,6
Extinct Water Vole	*Arvicola cantiana*	50	Fallow Deer	*Dama dama*	2,6
Brown Bear	*Ursus arctos*	50	Straight Tusked Elephant	*Palaeoloxodon antiquus*	2,4
Fallow Deer	*Dama dama*	50	Brown Bear	*Ursus arctos*	2,3
CLUSTER 8. NUMBER OF FAUNAS = 2. SITES: Thatcham, Starr Carr.					
European Hedgehog	*Erinaceus europaeus*	100	European Hedgehog	*Erinaceus europaeus*	21
Man	*Homo sapiens*	100	Elk	*Alces alces*	21
Beaver	*Castor fiber*	100	Red Fox	*Vulpes vulpes*	14
Wolf	*Canis lupus*	100	Badger	*Meles meles*	14
Red Fox	*Vulpes vulpes*	100	Pine Martin	*Martes martes*	14
Badger	*Meles meles*	100	Wild cat	*Felis silvestris*	14
Pine Martin	*Martes martes*	100	Rabbit	*Oryctolagus cuniculus*	10,5
Wild Car	*Felis silvestris*	100	Wild Boar	*Sus scrofa*	8,4
Wild Boar	*Cervus elaphus*	100	Water Vole	*Arvicola terrestris*	7,0
Roe Deer	*Capreolus capreolus*	100	Common Shrew	*Sorex araneus*	5,2
Elk	*Alces alces*	100	Mole	*Talpa europaea*	5,2
Aurochs	*Bos primigenius*	100	Beaver	*Castor fiber*	4,7

Species Common Name	Species Latin Name	% Occurrence	Species Common Name	Species Latin Name	Binary Frequency Ratio
CLUSTER 9. NUMBER OF FAUNAS = 1. SITE: Hoxne.					
All species have 100% occurrence, as only one fauna in cluster. (See Appendix 2, Table A3.2, for species list.)			Macaque Monkey	*Macaca sp.*	21
			Common Shrew	*Sorex araneus*	10.5
			Russian Desman	*Desmana moschata*	10.5
			Norway Lemming	*Lemmus lemmus*	10.5
			Extinct Beaver	*Trogontherium cuvieri*	8.4
			Roe Deer	*Capreolus capreolus*	8.4
			Field Vole	*Microtus agrestis*	5.2
			Fallow Deer	*Dama dama*	5.2
			Man	*Homo sapiens*	3.8
CLUSTER 10. NUMBER OF FAUNAS = 3. SITES: Aveley, Harkstead, Stutton.					
Bank Vole	*Clethrionomys glareolus*	100	Water Shrew	*Neomys fodiens*	14
Straight Tusked Elephant	*Palaeoloxodon antiquus*	100	Lesser White Toothed Shrew	*Crocidura cf. Suaveolens*	14
Mammoth	*Mammuthus primigenius*	100	Common Shrew	*Sorex araneus*	3.5
Horse	*Equus ferus*	100	Bank Vole	*Clethrionomys glareolus*	3.5
Red Deer	*Cervus elaphus*	100	Field Vole	*Microtus agrestis*	3.5
Bison	*Bison priscus*	100	Straight Tusked Elephant	*Palaeoloxodon antiquus*	3.2
Extinct Water Vole	*Arvicola cantiana*	67	Mammoth	*Mammuthus primigenius*	2.6
Field Vole	*Microtus agrestis*	67	Red Deer	*Cervus elaphus*	2.1
CLUSTER 11?. NUMBER OF FAUNAS = 4. SITES: Selsey, Sewerby, Bobbitshole, Wallingford.					
Horse	*Equus ferus*	75	Water Vole	*Arvicola terrestris*	3.5
Beaver	*Castor fiber*	50	Norway Lemming	*Lemmus lemmus*	2.6
Extinct Water Vole	*Arvicola cantiana*	50	Tundra Vole	*Microtus gregalis*	2.6
Straight Tusked Elephant	*Palaeoloxodon antiquus*	50	Spotted Hyaena	*Crocuta crocuta*	2.6
Steppe Rhino	*Dicerorhinus hemitoechus*	50	Beaver	*Castor fiber*	2.3
CLUSTER 12? NUMBER OF FAUNAS = 5. SITES: Stoke Tunnel, Marsworth (Lower Channel), Wretton, Tattershall Castle, Isleworth.					
Wolf	*Canis lupus*	100	Arctic Fox	*Alopex lagopus*	8.4
Brown Bear	*Ursus arctos*	100	Brown Bear	*Ursus arctos*	4.7
Mammoth	*Mammuthus primigenius*	100	Tundra Vole	*Microtus gregalis*	4.2
Horse	*Equus ferus*	100	Extinct Caballine Horse	*Equus caballus sp.*	4.2
Bison	*Bison priscus*	100	Wolf	*Canis lupus*	3.5
Woolly Rhino	*Coelodonta antiquitatis*	80	Reindeer	*Rangifer tarandus*	3.2
Northern Vole	*Microtus oeconomus*	60	Woolly Rhino	*Coelodonta antiquitatis*	3.0
Reindeer	*Rangifer tarandus*	60	Northern Vole	*Microtus oeconomus*	2.8
Tundra Vole	*Microtus gregalis*	40	Mammoth	*Mammuthus primigenius*	2.6
Lion	*Panthera leo*	40	Bison	*Bison priscus*	2.0

Species Common Name	Species Latin Name	% Occurrence	Species Common Name	Species Latin Name	Binary Frequency Ratio

CLUSTER 13. NUMBER OF FAUNAS = 6.
SITES: Homersfield, Baginton-Lillington Gravels, Upton Warren, Kirkby-on-Basin, Beckford, Coston.

Mammoth	*Mammuthus primigenius*	100	Woolly Rhino	*Coelodonta antiquitatis*	3,8
Woolly Rhino	*Coelodonta antiquitatis*	100	Arctic Lemming	*Dicrostonyx torquatus*	3,5
Bison	*Bison*	100	Reindeer	*Rangifer tarandus*	3,5
Horse	*Equus ferus*	83	Musk Ox	*Ovibos moschatus*	3,5
Reindeer	*Rangifer tarandus*	67	Mammoth	*Mammuthus primigenius*	2,6
Red Deer	*Cervus elaphus*	33	Bison	*Bison priscus*	2,0
Giant Deer	*Megaceros giganteus*	33			

These three faunal groups are clearly identifiable within Cluster 2; therefore the within-cluster structure of Cluster 2 may well have temporal meaning. Cluster 3 contains three faunas from West Runton (the Cromerian type site) and one fauna from Ostend. As would be expected, the Ostend fauna clusters further apart than the three West Runton faunas.

Cluster 4 probably results from taphonomic factors. The two sites (Sugworth and Swanton Morley) contain species that are respectively indicative of a Cromerian and last interglacial complex age. However they are both water lain deposits with atypical faunas. For example, although *Hippopotamus amphibius* is present at Swanton Morley, most of the other large mammal species normally associated with this species are absent. Instead a rich rodent fauna is recorded. It is therefore unsurprising that these two atypical faunas have clustered together despite their age differences, since they have been influenced by similar taphonomic factors.

The Cluster 5 faunas have all been assigned a Hoxnian age. However the Swanscombe lower loam and gravel faunas cluster away from the Ingress Vale and Clacton faunas. This may be indicative that these faunas are of different ages or that they have different taphonomies. Kerney (1971) and Sutcliffe & Kowalski (1976) have suggested that the Clacton and Ingress Vale deposits are younger than the Swanscombe lower loam deposits, but whether they represent a later stage in the same interglacial or different interglacials is problematic.

The association of the Swanscombe upper middle gravel and Crayford sites which form Cluster 6 is interesting. The famous Swanscombe Hominid skull was recovered from the base of the upper middle gravel (Oakley 1952) and the associated molluscan fauna is indicative of cooler conditions than the lower loam (Kerney 1971). The mammalian fauna contains species indicative of both warm and cold conditions and has been interpreted as either belonging to the closing stages of the Hoxnian interglacial or to a un-named mid Pleistocene interglacial (Wymer 1974, Roe 1981). The Crayford mammal fauna is also intriguing, containing both 'cold' and 'warm' species, and the associated molluscan fauna contains such thermophiles as *Corbicula fluminalis* and *Belgrandia marginata*, suggesting full interglacial conditions (Kennard 1944). The Crayford site has often been assigned to the closing stages of the Ipswichian (Stuart 1976,1982, Roe 1981), although there is little evidence for this; it seems more likely that both these sites belong to a post Hoxnian mid Pleistocene interglacial, although the simultaneous presence of Musk Ox and *Corbicula fluminalis* implies extremely continental conditions (A.P. Currant *pers comm*).

Cluster 7 is characterised by species typical of the 'last interglacial' Hippo faunas which have been uranium-series dated to C.125000 years BP at Victoria Cave (see Chapter III). The clustering of the Ilford site from which Hippo is absent does not lend support to Sutcliffe's (1975) suggestion that this site is older than Trafalgar Square.

Cluster 8 is a typical early Holocene fauna which has been described in detail by Yaldin (1982).

Cluster 9 contains only the Hoxne site and this fauna is by definition Hoxnian in age. Although the Cluster 9 Hoxne fauna and the Cluster 5 Clacton, Ingress Vale and Swanscombe lower loam both have certain species in common (eg Macaque Monkey, Fallow Deer and the extinct Beaver *Trogontherium cuvieri*) there are considerable differences between these faunas. Sutcliffe (1986) has suggested that the Hoxne fauna may be from a later mid Pleistocene (Hoxnian) interglacial than the Swanscombe loam, Clacton and Ingress Vale faunas.

Cluster 10 is characterised by sites containing the Hippo less Horse and Mammoth faunas that Sutcliffe (1975,1976) has argued are mid Pleistocene in age and have been incorrectly incorporated into the upper Pleistocene Ipswichian interglacial stage. The weak association of the Hoxne fauna with this cluster lends support to the idea of a mid Pleistocene age for this fauna.

Cluster 11 contains the sparse fauna from the Bobbitshole site which is by definition Ipswichian (pollen zones WO-IIb). Its association with the Selsey (pollen zone WO11a) and Stutton (pollen zone 111-1V?) sites is non-controversial. The Wallingford Fan gravel faunas have been tentatively assigned to the Anglian cold stage on the basis of their apparent gradation into the Black Park Terrace of the Thames. However the geomorphology is not certain (Horton & Whittow 1977). The clustering of the Wallingford fauna with that from Bobbitshole would suggest that it dates from the cold stage preceding the Ipswichian.

Clusters 12 and 13 are all sites with cold stage faunas, most of which are of Devensian age. However a number of mid Pleistocene sites (Homersfield, Baginton-Lillington Gravels, Marsworth (lower channel) and possibly Stoke Tunnel) have also clustered out in these groups, confirming the broad similarity of cold stage faunas of different ages (Stuart 1982). The close association of the Marsworth (lower channel) and Stoke Tunnel faunas lends further support to Sutcliffe's (1985) views that the Stoke Tunnel fauna is pre-Ipswichian in age. Stuart (1976, 1982) has assigned this fauna to Ipswichian pollen stage Ip 4. However the Marsworth (lower channel) fauna undoubtedly dates from the middle Pleistocene (see Chapter V).

In conclusion the cluster analysis of the UK 'open' site mammalian faunas generally supports the Quaternary mammalian chronology proposed by Sutcliffe (1975, 1985; Sutcliffe & Kowalski (1976) and Mayhew (1985), but it is often incompatible with the mammalian chronology of Stuart (1976, 1982) which largely uses the pollen record as a stratigraphic yardstick.

The UK 'Cave' Site Record

The dendrogram of the Ward's method solution presents a complex picture (Figure 6.6). As with the 'open' site cluster analysis, no obvious optimum solution is present. The cluster diagnostic statistics Table 6.7) show that all cluster solutions from 2 to 17 inclusive are likely to be statistically valid, and that similarity matrix distortion levels are acceptable.

Cluster 1 (Table 6.8) is formed from the Kent's Cavern (B1) and Dovehole faunas which, despite having no species in common, are less dissimilar from each other than from any of the other cave faunas. These sites therefore cannot be considered as a true cluster, but by comparing their their faunas with those from the open sites, the most likely correlations are Dove Hole with one of the lower Pleistocene Cluster 1 or 2 faunas and Kent's Caverns (B1) with the Cromerian Cluster 3 or the Sugworth fauna.

The Cluster 2 and 3 faunas are most similar to the open site post-glacial faunas. However the Cluster 2 faunas contain more cold tolerant species than the Cluster 3 faunas, possibly implying that they date from earlier in the Holocene interglacial. A major difference between the two clusters is the 100% occurrence of Lynx in the Cluster 2 sites compared to the 100% occurrence of Wild Cat in the Cluster 3 sites. Jenkinson (1984) has argued that Lynx was present in Britain only during the late Devensian/early Flandrian period. However it must be noted that fossil remains of Lynx are frequently only distinguished from Wild Cat by their larger size (Stuart 1982), so misidentifications are possible.

The Cluster 4 faunas are typical of the classic mid Devensian large mammal assemblages which are characterised by the presence of Mammoth, Woolly Rhino, Spotted Hyaena and Lion. They mainly differ from the similar open site faunas by the presence of a greater number of carnivore species.

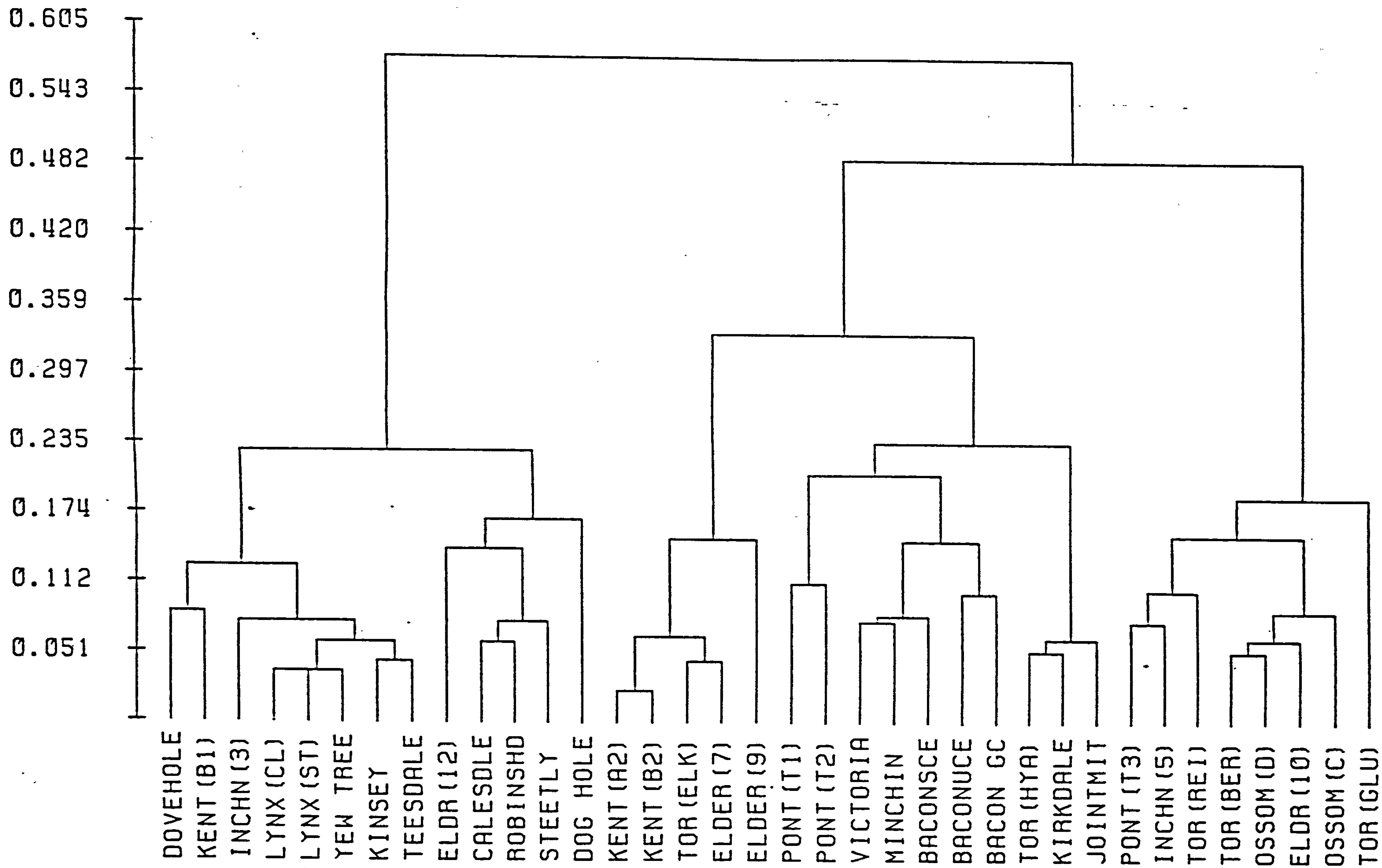


FIGURE 6.6 : Dendrogram of UK 'cave' site mammal data clustered by Ward's method from a Euclidean distance matrix.

TABLE 6.7 : CLUSTER DIAGNOSTIC STATISTICS FOR WARD'S METHOD USING A EUCLIDEAN DISTANCE SIMILARITY MATRIX CALCULATED FROM THE UK 'CAVE' SITE FAUNAL DATA

Mean = 0,132
Standard Deviation = 0,121

PREDICTED CLUSTERS	MAXIMUM VALUE OF REALISED DEVIATES USING RULE 1 OR RULE 2	t-VALUE (39 Degrees of Freedom)
2	3,66	21,3
3	3,77	22,0
4	2,30	13,4
5	0,90	5,2
6	1,13	6,6
7	0,99	5,8
8	0,84	4,9
9	0,30	1,7
10	0,19	1,1
11	0,16	0,9
12	0,88	5,1
13	1,19	6,9
14	1,04	6,1
15	0,59	3,4
17	0,90	5,2

Cophenetic Correlation = 0,48
Delta 0 = 2,00
Delta 1 = 2,48
Delta 2 = 2,29

TABLE 6.8 : UK 'CAVE' SITES CLUSTER ANALYSIS RESULTS

Species Common Name	Species Latin Name	% Occurrence	Species Common Name	Species Latin Name	Binary Frequency Ratio
CLUSTER 1. NUMBER OF FAUNAS = 2. SITES: Dove Hole, Kent's Cavern (B1).					
No species common to both sites.			Extinct Pine Vole	*Pitymys gregaloides*	18
			Sabre Toothed Cat	*Homotherium latidens*	18
			Sabre Toothed Cat	*Homotherium sainzelli*	18
			Extinct Elephant	*Archidiskodon meridionalis*	18
			Gomphothere Mastodont	*Anancus arvernensis*	18
			Extinct Callabine Horse	*Equus cabillus sp.*	18
CLUSTER 2. NUMBER OF FAUNAS = 6.. SITES: Inchnadamff (Bed 3), Lynx Cave (Clwyd, Bed C), Lynx Cave (Staffs), Yew tree, Kinsey, Teesdale Fissure.					
Lynx	*Lynx lynx*	100	Otter	*Lutra lutra*	6
Wolf	*Canis lupus*	67	Lynx	*Lynx lynx*	4
Red Fox	*Vulpes vulpes*	67	Pole Cat	*Mustela putorius*	3
Aurochs	*Bos primigenius*	67	Aurochs	*Bos primigenius*	2,2
Reindeer	*Rangifer tarandus*	50	Roe deer	*Capreolus capreolus*	2,0
Wild Boar	*Sus scrofa*	33			
Red Deer	*Cervus elaphus*	33			
Roe Deer	*Capreolus capreolus*	33			
CLUSTER 3. NUMBER OF FAUNAS = 5. SITES: Elderbush (Layer 12), Cales Dale, Robin's Hood, Steetley, Dog Hole.					
Wild Cat	*Felis sylvestris*	100	European Hedgehog	*Erinaceus europaeus*	7,2
Wolf	*Canis lupus*	80	Natterer's Bat	*Myotis nattereri*	7,2
Red Fox	*Vulpes vulpes*	80	Barbastelle Bat	*Barbastella barbastella*	7,2
Badger	*Meles meles*	80	Elk	*Alces alces*	7,2
Red Deer	*Cervus elaphus*	80	Sheep/Goat	*Ovis/Capra sp.*	7,2
Aurochs	*Bos primigenius*	80	Wild Cat	*Felis sylvestris*	6,0
Bank vole	*Clethrionomys glareolus*	60	Mole	*Talpa europaea*	3,6
Lynx	*Lynx lynx*	60	Whiskered Bat	*Myotis mystacinus*	3,6
Horse	*Equus ferus*	60	Long-eared Bat	*Plecotus australalus*	3,6
Wild Boar	*Sus scrofa*	60	Polecat	*Mustela putorius*	3,6
Roe Deer	*Capreolus capreolus*	60	Roe Deer	*Capreolus capreolus*	3,6

Species Common Name	Species Latin Name	% Occurrence	Species Common Name	Species Latin Name	Binary Frequency Ratio
CLUSTER 4. NUMBER OF FAUNAS = 5. SITES: Kent's Caverns (A2,B2), Elderbush (Layers 7 & 9), Tornewton (Elm Stratum).					
Red Fox	*Vulpes vulpes*	100	Woolly Rhino	*Coelodonta antiquitatis*	5,8
Brown Bear	*Ursus arctos*	100	Giant Deer	*Megaceros giganteus*	4,5
Spotted Hyaena	*Crocuta crocuta*	100	Common Vole	*Microtus arvalis*	3,6
Giant Deer	*Megaceros giganteus*	100	Cave Bear	*Ursus deningeri/spelaeus*	3,6
Bison	*Bison priscus*	100	Mammoth	*Mammuthus primigenius*	3,6
Wolf	*Canis lupus*	80	Spotted Hyaena	*Crocuta crocuta*	2,6
Lion	*Panthera leo*	80	Lion	*Panthera leo*	2,4
Horse	*Equus ferus*	80	Horse	*Equus ferus*	2,4
Woolly Rhino	*Coelodonta antiquitatis*	80	Bison	*Bison priscus*	2,3
CLUSTER 5. NUMBER OF FAUNAS = 2. SITES: Pontnewydd (Types 1 & 2).					
Tundra Vole	*Microtus gregalis*	100	Steppe Pika	*Ochotona pusilla*	18
Wolf	*Canis lupus*	100	Leopard	*Panthera pardus*	18
Brown Bear	*Ursus arctos*	100	Extinct Rhino	*Dicerorhinus kirchbergensis*	18
Leopard	*Panthera pardus*	100	Beaver	*Castor fiber*	9
Horse	*Equus ferus*	100	Extinct Water Vole	*Arvicola cantiana*	3,6
Steppe Rhino	*Dicerorhinus hemitoechus*	100	Steppe Rhino	*Dicerorhinus hemitoechus*	3,6
CLUSTER 6. NUMBER OF FAUNAS = 5. SITES: Victoria Cave, Minchin Hole, Bacon Hole (Upper Cave Earth, Grey Clays, Sandy Cave Earth).					
Spotted Hyaena	*Crocuta crocuta*	80	Extinct Water Vole	*Arvicola cantiana*	4,3
Steppe Rhino	*Dicerorhinus hemitoechus*	80	Straight Tusked Elephant	*Palaeoloxodon antiquus*	4,3
Red Deer	*Cervus elaphus*	80	Mammoth	*Mammuthus primigenius*	3,6
Field Vole	*Microtus agrestis*	60	Fallow Deer	*Dama dama*	3,6
Northern Vole	*Microtus oeconomus*	60	Steppe Rhino	*Dicerorhinus hemitoechus*	2,9
Wood Mouse	*Apodemus sylvaticus*	60	Common Shrew	*Sorex araneus*	2,4
Lion	*Panthera leo*	60	Wood Mouse	*Apodemus sylvaticus*	2,2
Straight Tusked Elephant	*Palaeoloxodon antiquus*	60	Spotted Hyaena	*Crocuta crocuta*	2,1
Fallow Deer	*Dama dama*	60			

Species Common Name	Species Latin Name	% Occurrence	Species Common Name	Species Latin Name	Binary Frequency Ratio
CLUSTER 7. NUMBER OF FAUNAS = 3. SITES: Tornewton (Hyaena Stratum), Kirkdale, Joint Mitnor.					
Water Vole	*Arvicola terrestris*	100	Brown Hare	*Lepus capensis*	12
Field Vole	*Microtus agrestis*	100	Hippo	*Hippopotamus amphibius*	7,2
Wolf	*Canis lupus*	100	Stoat	*Mustela erminea*	6,0
Red Fox	*Vulpes vulpes*	100	Fallow Deer	*Dama dama*	6,0
Lion	*Panthera leo*	100	Steppe Rhino	*Dicerorhinus hemitoechus*	3,6
Brown Bear	*Ursus arctos*	100	Straight Tusked Elephant	*Palaeoloxodon antiquus*	4,8
Spotted Hyaena	*Crocuta crocuta*	100	Field Vole	*Microtus agrestis*	3,0
Steppe Rhino	*Dicerorhinus hemitoechus*	100	Lion	*Panthera leo*	3,0
Hippo	*Hippopotamus amphibius*	100	Giant Deer	*Megaceros giganteus*	3,0
Red Deer	*Cervus elaphus*	100	Water Vole	*Arvicola terrestris*	2,6
Fallow Deer	*Dama dama*	100	Spotted Hyaena	*Crocuta crocuta*	2,6
Aurochs	*Bos primigenius*	100	Wood Mouse	*Apodemus sylvaticus*	2,4
Wood Mouse	*Apodemus sylvaticus*	67	Red Deer	*Cervus elaphus*	2,4
Straight Tusked Elephant	*Palaeoloxodon antiquus*	67			
Giant Deer	*Megaceros giganteus*	67			
CLUSTER 8. NUMBER OF FAUNAS = 7. SITES: Pontnewydd (Type 3), Inchnadamff (Bed 5), Elder Bush (Layer 10), Tornewton (Reindeer & Bear Stratum), Ossoms Cave (Beds C,D).					
Arctic Lemming	*Dicrostonyx torquatus*	100	Musk Ox	*Ovibos moschatus*	5,1
Northern Vole	*Microtus oeconomus*	86	Arctic Lemming	*Dicrostonyx torquatus*	4,0
Water Vole	*Arvicola terrestris*	71	Mountain Hare	*Lepus timidus*	3,4
Field Vole	*Microtus agrestis*	71	Norway Lemming	*Lemmus lemmus*	2,9
Mountain Hare	*Lepus timidus*	57			
Norway Lemming	*Lemmus lemmus*	57			
Bank Vole	*Clethrionomys glareolus*	57			
Brown Bear	*Ursus arctos*	57			
Reindeer	*Rangifer tarandus*	57			
Bison	*Bison priscus*	42			
CLUSTER 9. NUMBER OF FAUNAS = 1. SITE: Tornewton (Glutton Stratum).					
All species have 100% occurrence as only one fauna in cluster. (See Appendix 2, Table A3.1 for species list.)			Common Hamster	*Cricetus cricetus*	36
			Extinct Hamster	*Allocricetus bursae*	36
			Extinct Otter	*Aonyx antiqua*	36
			Wolverine	*Gulo gulo*	36
			Steppe Lemming	*Lagurus lagurus*	36
			Snow Vole	*Microtus oeconomus var nivalis*	18
			Norway Lemming	*Lemmus lemmus*	5,1
			Arctic Lemming	*Dicrostonyx torquatus*	4,0
			Bank Vole	*Clethrionomys glareolus*	4,0
			Steppe Rhino	*Dicerorhinus hemitoechus*	3,6

The Pontnewydd type 1 and 2 faunas that form Cluster 5 are mid Pleistocene in age and are associated with a number of uranium series dates (see chapter III). The faunas are similar to several of the open site mid Pleistocene faunas in containing species adapted to both steppe and wooded environments.

The Cluster 6 and 7 faunas are characteristic of a last interglacial complex age, with Cluster 7 being characterised by the interglacial 'Hippo' faunas Sutcliffe (1960) has described as *"dating from the warmest part of the Eemian"*. These appear to be distinct within cluster structure in Cluster 6, with Victoria Cave, Minchin Hole and Bacon Hole sandy cave earth forming one group, and Bacon Hole upper cave earth and grey clays forming another.

The Cluster 8 faunas are interesting in that they most probably are of mid- Devensian age but are markedly different from the classic large mammal mid-Devensian faunas (Cluster 5). The number of species is restricted and they are virtually exclusively 'hardy' mammals adapted to true cold arctic environments. It seems possible that the Cluster 5 large mammal faunas are representative of interstadial conditions whereas elements of the Cluster 8 cold adapted fauna were present during the intervening stadial environments.

The Tornewton (Glutton Stratum) fauna forms Cluster 9. It is mid-Pleistocene in age as it underlies the Hyaena stratum with its last interglacial complex mammal assemblage. Sutcliffe & Kowalski (1976) have argued that a number of the restricted species found in the Glutton Stratum are indicator species for mid-Pleistocene cold/steppe periods. They are:

1) Snow Vole *(Microtus oeconomus var nivalis)*

2) Hamsters *(Cricetus cricetus & Allocricetus bursae)*

3) Steppe Lemming *(Lagurus lagurus)*

4) Extinct Otter *(Aonyx antiqua)*

In conclusion the UK cave mammal record with its well preserved 'interstadial and stadial' faunas complements the open site mammal record which contains many 'interglacial' assemblages. By comparing these two records with the mixed open and cave site faunas from the Mendip Region it should be possible to tentatively place the Mendip region sites within a mammalian biostratigraphical framework.

The Mendip Region Mammal Fauna Sites

The dendrogram of Ward's solution using a similarity matrix calculated from the presence/absence data from the Mendip region mammal sites, presents a very complex picture, as was expected. (Figure 6.7) The cluster diagnostic statistics show no obvious optimum solution exists and that all cluster solutions between 2 and 13 clusters are probably valid (Table 6.9). The amount of similarity matrix distortion is probably acceptable but is higher than for the UK open and cave site solutions. This may be due to the presence of both open and cave sit assemblages in the Mendip record, which means that significant taphonomic variation is also present along with the temporal variation.

Clusters 1 and 8 (Table 6.10) are made up of seven Westbury-sub-Mendip faunas and one assemblage from Goatchurch Cavern. The Goatchurch Cavern fauna is undoubtedly wrongly classified and is probably upper Pleistocene in age. It has clustered with the Westbury faunas because it is more dissimilar to the other Mendip

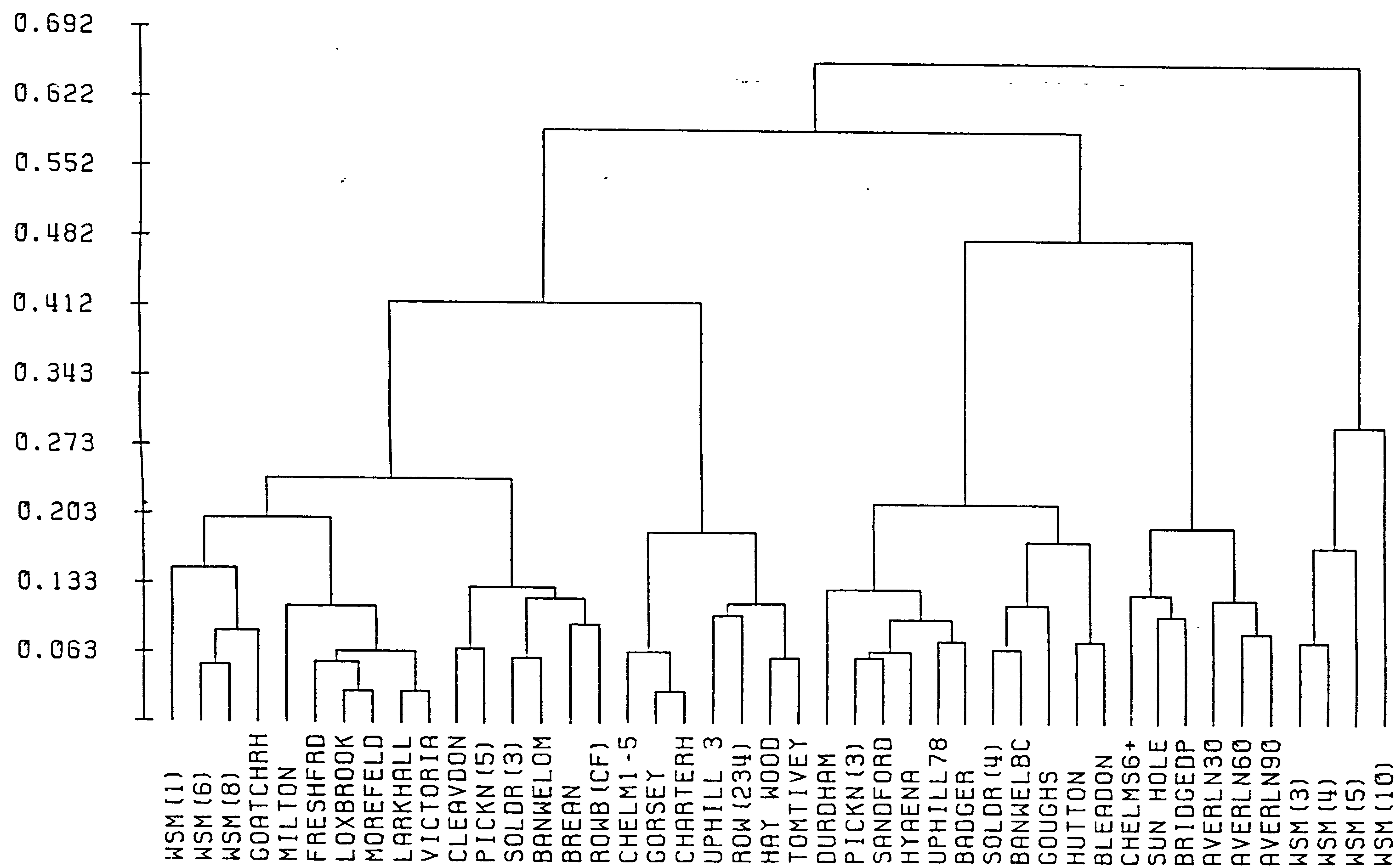


FIGURE 6.7 : Dendrogram of Mendip region mammal data clustered by Ward's method from a Euclidean distance matrix.

region assemblages and the possibility of faunal mixing and misidentification cannot be excluded. Bishop (1982) has compared the Westbury-sub-Mendip faunas with those from other lower and mid Pleistocene sites in Europe and concluded that the Bed 1 fauna is lower Pleistocene and the Beds 2 -10 faunas belong to an un-named post Cromerian but pre Hoxnian interglacial.

The Cluster 2 faunas are all from the Bath gravel sites, with the exception of the Milton Hill fauna which is classified much further away. The assemblage contains characteristic species of both mid Devensian and last interglacial complex faunas and could result from mid Devensian reworking of older gravel deposits. Boreland (1985) has assumed a 'Wolstonian' age for these gravels on geomorphological grounds; however none of the species present would support this interpretation.

Clusters 3 and 6 are mixed assemblages containing faunas that can be assigned to the mid Pleistocene cold/steppe period, the mid Devensian large mammal faunas and the late glacial respectively. They have clustered together because they have a number of cosmopolitan cold adapted species in common (Wolf, Red Fox, Reindeer etc) and because they are dissimilar to the other Mendip region faunas. They therefore cannot be considered to be correctly classified. By comparing these faunas with the UK open and cave site results it seems likely that Hutton, Banwell Bone Cave, Clevedon and Bleadon Cavern (in part) date from the mid Pleistocene cold period of Tornewton (Glutton) stratum age, that Soldiers Hole (layer 4), Picken's Hole (layer 5) and possibly Brean Down (Beds 11 to 13) date from the mid Devensian, and that Banwell Ochre Mines, Rowerbarrow Cavern (cemented floor), Soldiers Hole (layer 3) and Gough's Cave date from the late glacial period.

TABLE 6.9 : CLUSTER DIAGNOSTIC STATISTICS FOR WARD'S SOLUTION USING A EUCLIDEAN DISTANCE SIMILARITY MATRIX CALCULATED FROM THE MENDIP REGION MAMMAL DATA

Mean = 0,149
Standard Deviation = 0,142

PREDICTED CLUSTERS	MAXIMUM VALUE OF REALISED DEVIATES USING RULES 1 & 2	t-VALUE (42 Degrees of Freedom)
2	3,6	22,7
3	3,25	20,5
4	3,13	19,8
5	3,48	22,0
6	1,92	12,1
7	1,11	7,0
8	0,83	5,2
9	0,67	4,2
10	0,61	3,8
11	0,90	5,7
12	0,99	6,3
13	1,42	9,0

Cophenetic Correlation = 0,59
Delta 0 = 1,92
Delta 1 = 2,31
Delta 2 = 2,22

TABLE 6.10: MENDIP REGION SITES CLUSTER ANALYSIS RESULTS

CLUSTER 1. NUMBER OF FAUNAS = 4. SITES: Westbury-sub-Mendip (Beds 1,6,8), Goatchurch Cavern.

Species Common Name	Species Latin Name	% Occurrence	Species Common Name	Species Latin Name	Binary Frequency Ratio
Deningeri's Bear	*Ursus deningeri*	75	Extinct Water Vole	*Mimomys savini*	11,0
Bison	*Bison priscus*	75	Extinct Vole	*Microtus (allophaiomys) sp.*	11,0
Extinct Jaguar	*Panthera gombaszogensis*	50	Extinct Hyaena	*Hyaena brevirostris*	11,0
			Extinct Bison	*Bison schoetensacki*	11,0
			Extinct Pine vole	*Pitymys arvaloides*	5,5
			Extinct Cat	*Felis cf. lunensis*	5,5
			Extinct Rhino	*Dicerorhinus etruscus*	5,5
			Extinct Jaguar	*Panthera gombaszogensis*	4,4
			Extinct Pine Vole	*Pitymys gregaloides*	3,7
			Deningeri's Bear	*Ursus deningeri*	3,3
			Beaver	*Castor fiber*	2,75

CLUSTER 2. NUMBER OF FAUNAS = 6. SITES: Milton Hill, Freshford, Loxbrook, Morefield, Victoria Pit, Larkhall.

Species Common Name	Species Latin Name	% Occurrence	Species Common Name	Species Latin Name	Binary Frequency Ratio
Mammoth	*Mammuthus primigenius*	83	Musk Ox	*Ovibos moschatus*	7,3
Woolly Rhino	*Coelodonta antiquitatis*	83	Straight Tusked Elephant	*Palaeoloxodon antiquus*	4,4
Reindeer	*Rangifer tarandus*	83	Woolly Rhino	*Coelodonta antiquitatis*	3,7
Aurochs	*Bos Primigenius*	83	Hippo	*Hippopotamus amphibius*	3,7
Straight Tusked Elephant	*Palaeoloxodon antiquus*	50	Mammoth	*Mammuthus primigenius*	2,4
Horse	*Equus ferus*	33	Aurochs	*Bos primigenius*	2,3
Wild Boar	*Sus scrofa*	33			
Red Deer	*Cervus elaphus*	33			
Giant Deer	*Megaceros giganteus*	33			
Bison	*Bison priscus*	33			

CLUSTER 3. NUMBER OF FAUNAS = 6.
SITES: Pickens Hole (Layer 5), Cleavdon Cave, Soldiers Hole (Layer 3), Banwell Ochre Mines, Brean Down, Rowberrow Cavern (Cemented Floor).

Species Common Name	Species Latin Name	% Occurrence	Species Common Name	Species Latin Name	Binary Frequency Ratio
Tundra Vole	*Microtus gregalis*	67	Snow Vole	*Microtus oeconomus var*	3,67
Wolf	*Canis lupus*	67	Steppe Pika	*Ochotona pusilla*	3,14
Reindeer	*Rangifer tarandus*	67	Arctic Fox	*Alopex lagopus*	2,44
Mountain Hare	*Lepus timidus*	50	Tundra Vole	*Microtus gregalis*	2,10
Steppe Pika	*Ochotona pusilla*	50			
Arctic Lemming	*Dicrostonyx torquatus*	50			
Northern Vole	*Microtus oeconomus*	50			
Brown Bear	*Ursus arctos*	50			
Horse	*Equus ferus*	50			
Water Vole	*Arvicola terrestris*	33			
Field Vole	*Microtus agrestis*	33			
Arctic Fox	*Alopex lagopus*	33			
Red Fox	*Vulpes vulpes*	33			
Red Deer	*Cervus elaphus*	33			
Bison	*Bison priscus*	33			

Species Common Name	Species Latin Name	% Occurrence	Species Common Name	Species Latin Name	Binary Frequency Ratio
CLUSTER 4. NUMBER OF FAUNAS = 7. SITES: Chelms Coombe (Spits 1-5), Gorsey Bigbury, Charterhouse Warren Farm, Uphill 3, Rowberrow (Layers 1,2,3),Haywood Cave, Tom Tivey's Hole (Layers 1-3).					
Wild Boar	*Sus scrofa*	100	Fallow Deer	*Dama dama*	6
Wolf	*Canis lupus*	86	Sheep/Goats	*Ovis/Capra sp.*	5,0
Aurochs	*Bos primigenius*	86	Rabbit	*Oryctolagus cuniculus*	4,7
Horse	*Equus ferus*	71	Roe Deer	*Capreolus capreolus*	4,2
Red Deer	*Cervus elaphus*	71	Wild cat	*Felis sylvestris*	3,6
Wood Mouse	*Apodemus sylvaticus*	57	Common Shrew	*Sorex araneus*	3,1
Red Fox	*Vulpes vulpes*	57	Pigmy Shrew	*Sorex minutus*	3,1
Wild Cat	*Felis sylvestris*	57	Wild Boar	*Sus scrofa*	2,9
Badger	*Meles meles*	57	Pole Cat	*Mustela putorius*	3,1
Roe Deer	*Capreolus capreolus*	57	Wood Mouse	*Apodemus sylvaticus*	2,5
Sheep/Goats	*Ovis/Capra.*	57	Badger	*Meles meles*	2,5
Rabbit	*Oryctolagus cuniculus*	43	Weasel	*Mustela nivalis*	2,5
Bank Vole	*Clethrionomys glareolus*	43	Aurochs	*Bos primigenius*	2,4
CLUSTER 5. NUMBER OF FAUNAS = 6. SITES: Durdham Down, Pickens Hole (Layer 3), Sandford Hill, Uphill (7 & 8), Badger Hole, Hyaena Den.					
Spotted Hyaena	*Crocuta crocuta*	100	Otter	*Lutra lutra*	7,3
Horse	*Equus ferus*	100	Steppe Rhino	*Dicerorhinus hemitoechus*	7,3
Brown Bear	*Ursus arctos*	83	Susliks	*Spermophilus sp.*	3,7
Lion	*Panthera leo*	83	Spotted Hyaena	*Crocuta crocuta*	3,7
Mammoth	*Mammuthus primigenius*	83	Woolly rhino	*Coelodonta antiquitatis*	3,7
Woolly Rhino	*Coelodonta antiquitatis*	83	Hippo	*Hippopotamus amphibius*	3,7
Reindeer	*Rangifer tarandus*	83	Lion	*Panthera leo*	2,8
Bison	*Bison*	83	Man	*Homo sapiens*	2,7
Red Fox	*Vulpes vulpes*	67	Mammoth	*Mammuthus primigenius*	2,4
Giant Deer	*Megaceros giganteus*	50	Giant Deer	*Megaceros giganteus*	2,0
CLUSTER 67. NUMBER OF FAUNAS = 5. SITES: Banwell Bone Cave, Soldiers Hole (Layer 4), Gough's Cave, Hutton Cavern, Bleadon Cavern.					
Wolf	*Canis lupus*	100	Water Shrew	*Neomys fodiens*	8,8
Red Fox	*Vulpes vulpes*	100	Extinct Hamster	*Allocricetus bursae*	8,8
Brown Bear	*Ursus arctos*	100	Leopard	*Panthera pardus*	8,8
Horse	*Equus ferus*	100	Susliks	*Spermophilus sp.*	4,4
Reindeer	*Rangifer tarandus*	100	Snow Vole	*Microtus oeconomus var nivalis*	4,4
Norway Lemming	*Lemmus lemmus*	80	Saiga antelope	*Saiga tartarica*	4,4
Lion	*Panthera leo*	60	Giant Deer	*Megaceros giganteus*	3,2
Red Deer	*Cervus elaphus*	80	Norway Lemming	*Lemmus lemmus*	
Giant Deer	*Megaceros giganteus*	80	Lion	*Panthera leo*	2,7
Bison	*Bison priscus*	80			

CLUSTER 7. NUMBER OF FAUNAS = 6.
SITES: Averline's Hole (0.90cm), Chelms Coombe (Spits 6-22), Sun Hole (Unit 1), Bridged Pot.

Species Common Name	Species Latin Name	% Occurrence	Species Common Name	Species Latin Name	Binary Frequency Ratio
Mountain Hare	*Lepus timidus*	100	Whiskered Bat	*Myotis mystalinus*	7,3
Water Vole	*Arvicola terrestris*	100	Bechstein's Bat	*Myotis bechsteini*	7,3
Red Fox	*Vulpes vulpes*	100	Lynx	*Lynx lynx*	7,3
Arctic Lemming	*Dicrostonyx torquatus*	83	Steppe Pika	*Ochotona pusilla*	4,2
Norway Lemming	*Lemmus lemmus*	83	Mole	*Talpa europaea*	3,7
Common Vole	*Microtus arvalis*	83	Wolverine	*Gulo gulo*	3,7
Tundra Vole	*Microtus gregalis*	83	Saiga antelope	*Saiga tartarica*	3,7
Brown Bear	*Ursus arctos*	83	Water Vole	*Arvicola terrestris*	3,4
Horse	*Equus ferus*	83	Common Vole	*Microtus arvalis*	3,3
Reindeer	*Rangifer tarandus*	83	Field Vole	*Microtus agrestis*	3,3
Steppe Pika	*Ochotona pusilla*	67	Norway Lemming	*Lemmus lemmus*	3,1
Bank Vole	*Clethrionomys glareolus*	67			
Field Vole	*Microtus agrestis*	67			
Northern Vole	*Microtus oeconomus*	67			

CLUSTER 8. NUMBER OF FAUNAS = 4. SITES: Westbury-sub-Mendip (Beds 3,4,5 & 10).

Species Common Name	Species Latin Name	% Occurrence	Species Common Name	Species Latin Name	Binary Frequency Ratio
Extinct Wolf	*Canis lupus mosbachensis*	100	European Hedgehog	*Erinaceus europaeus*	11
Deningeri's Bear	*Ursus deningeri*	100	Extinct Shrew	*Sorex runtonensis*	11
Bovid Species	*Bison sp.*	100	Extinct Shrew	*Sorex savini*	11
Long Eared Bat	*Plecotus austriacus*	75	Extinct Water Shrew	*Neomys newtoni*	11
Barbastelle Bat	*Barbastella barbastella*	75	Extinct Mole	*Talpa minor*	11
Extinct Dhole	*Xenocyon lycaonoides*	75	Desman	*Desmana moschata*	11
Extinct Jaguar	*Panthera gombaszogensis*	75	Extinct Vole	*Pliomys episcopalis*	11
Sabre-Toothed Cat	*Homotherium latidens*	75	Extinct Water Vole	*Arvicola cantiana*	11
Extinct Callabine Horse	*Equus caballus sp.*	75	Extinct Dhole	*Xenocyon lycaonoides*	11
Red Deer	*Cervus elaphus*	75	Sabre-Toothed Cat	*Homotherium latidens*	11
			Extinct Sheep	*Soergelia elizabethae*	11

The Cluster 4 faunas are all consistent with a Holocene age. The within-cluster structure shows that two faunal groups are present. Holocene faunal changes have been noted by Yalden (1982) but these changes will not be discussed as they are beyond the scope of this thesis.

The Cluster 5 faunas are effectively identical to the classic mid Devensian large mammal assemblages found at other UK sites. Although the Durdham Down site fauna is clearly misclassified within this cluster.

The Cluster 7 sites have all been assigned a late glacial age and the species present are generally similar to the Steppe Pika/Reindeer/Saiga antelope faunas that Stuart (1983) and Currant (1986) have argued are characteristic of mixed late glacial deposits which span the post Dimlington stadial/pre mid Holocene period.

This brief discussion has shown that there are two major outstanding problems with classifying the Mendip region faunas. These are the exact age of the:

1) last interglacial complex sites;
2) mid Pleistocene cold/steppe period sites.

The Age of Milton Hill and Durdham Down

The Milton Hill and Durdham Down faunal assemblages have few species in common and therefore unsurprisingly did not cluster together. However they both contain species that are consistent with a last interglacial complex age. In order to determine whether they belong to the same or different last interglacial complex periods, further cluster analysis was undertaken using all the UK last interglacial complex cave sites (Figure 6.8). The dendrogram shows that both

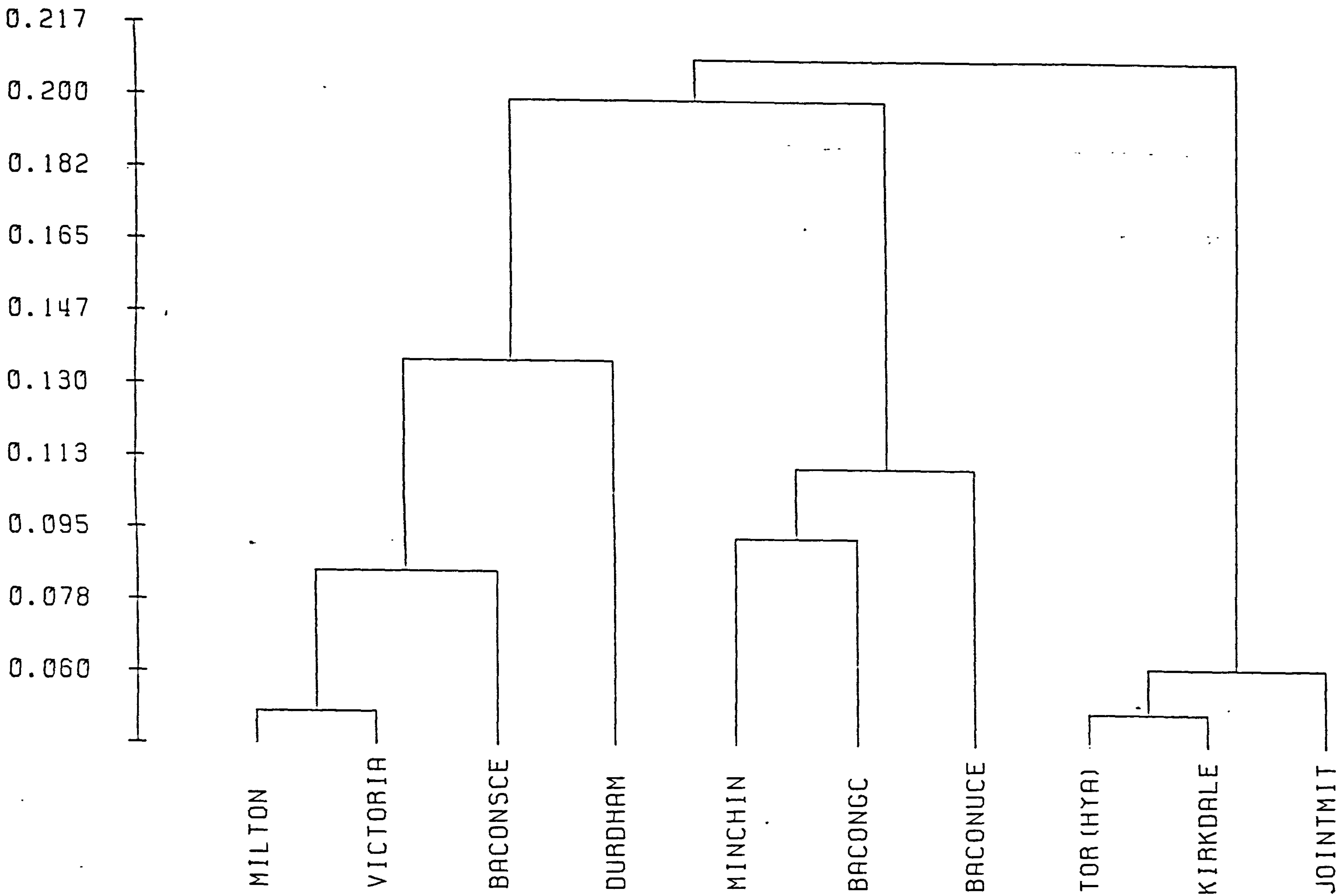


FIGURE 6.8 : Dendrogram of UK 'Last Interglacial Complex' cave site mammal data clustered by Ward's method from a Euclidean distance matrix.

Milton Hill and Durdham Down cluster out in the same group as Victoria Cave where the Hippo fauna has associated uranium series dates of C.125000 years BP. The three cluster solution is obviously optimal for these data and it is tempting to correlate these three faunal assemblages with the three 'last interglacial' speleothem growth periods (Chapter III). The Victoria Cave group would correlate with the Ip 3 (124000 years BP) peak, the Bacon Hole (Upper cave Earth) group with the Ip 1 peak (90500 years BP) and the Kirkdale Cave group with the Ip 2 (105000 years BP) peak. This would imply that *Hippopotamus amphibius* was present during the first two upper Pleistocene interglacials (Ip 3 and Ip 2) but not during the Ip 1 interglacial. However it must be stressed that the number of sites (10) is too small to reliably make these correlations. A much fuller study with more rigorous control of taphonomic factors would be required before firm conclusions could be drawn.

The Mid Pleistocene Cold/Steppe Faunas

Since only one other cave fauna (Tornewton glutton stratum) has been assigned to this stage, further cluster analysis by faunas would be uninformative. However the statistical association of the indicator species suggested by Sutcliffe (1976,1985) as characteristic of this period can be tested.

The mammal faunas were clustered by site for all the UK and Mendip region open and cave sites. The resulting solution is not shown because of its size but the relevant section of the minimum spanning tree for the similarity matrix is shown in Figure 6.9. The indicator species proposed by Sutcliffe (1976) are all closely associated with each other and form a homogenous grouping. The presence of Leopard (*Panthera pardus*) in this group is interesting as this species is not found at Tornewton. Leopard is only found in five UK sites: Robin Hood's Cave, Pontnewydd (Type I and II faunas), Hutton Cave, Bleadon Cave and Clevedon Cave. Robin Hood's Cave contains a mixed faunal assemblage which is thought to be mainly Devensian but the presence of Sabre-toothed Cat *(Homotherium latidens)* indicates that older deposits may have contaminated this fauna. Recently some speleothem remnants in Robin Hood's Cave have been uranium-series dated and pre last interglacial complex speleothem growth is present (P Rowe *pers comm)*. The Pontnewydd Types I and II faunas are both associated with a number of mid Pleistocene uranium series dates from speleothem (see chapter III). At Hutton and Clevedon Cave other mid Pleistocene indicator species are present with Leopard, and Hinton (1926) and Sutcliffe & Kowalski (1976) consider both these sites to be mid Pleistocene. The Bleadon Cavern fauna is mixed containing both warm and cold indicator species. Turner (1981) thought at least some of these faunas were Ipswichian from this study of the Horse teeth and Adams (1877-81) figures a Straight-tusked Elephant tooth from Bleadon cavern which is still in the British Museum (Natural History) collection (A.P. Currant *pers comm)*. Recently small mammal remains have been collected by the author from above and below a speleothem which grew during the mid Pleistocene (P.L. Smart *pers comm)*. It therefore seems possible that the Bleadon Cavern Leopard dates from the mid Pleistocene period. The Leopard *(Panthera pardus)* could well be a good indicator fossil for the mid Pleistocene cold/steppe period which the Banwell Bone Cave, Hutton, Clevedon and Bleadon Cavern (in part) faunas belong to.

FIGURE 6.9 : Minimum spanning tree results for mid Pleistocene cold/ steppe fauna indicator species

```
Wolverine ++++++++++Pine Martin            |++++++++++Common Hamster
          50%  |                           |    33%
               |                           |
               |+++++++++++Leopard         |++++++++++Extinct Hamster
               |    67%                         33%
               |                                      (Allocricetus
               |    67%                                 bursae)
               |+++++++++++Extinct Otter
               |
               |    33%
               |+++++++++++Snow Vole
```

In conclusion, seven distinct Pleistocene faunas can be identified from the Mendip region. Table 6.11 shows some of the possible correlations between the Mendip region faunas and those from other UK sites. It must be stressed that this biostratigraphy is tentative and that other equally valid stratigraphies can probably be constructed from the same data. However, it must be noted that this biostratigraphy has important archaeological implications. All the last interglacial complex sites from which significant numbers of hominid artifacts and bones (*Homo sapiens var neanderthalis*) are known, have been reassigned a mid Pleistocene age.

TABLE 6.11 : TENTATIVE BIOSTATIGRAPHY OF UK PLEISTOCENE MAMMAL FAUNAS BASED UPON CLUSTER ANALYSIS RESULTS (? denotes uncertain position)

	Pleistocene Stage Name/Period Type	UK Open Sites (excluding the Mendip Region)	UK cave Sites (excluding the Mendip Region)	Mendip Region Sites
Lower Pleistocene	PLIO/PLEISTOCENE	RED CRAG		
	BRAMERTONIAN	BLAKES PIT THORPE/NORWICH		
	EARLY BAVENTIAN	EAST BAVENTS	DOVE HOLE ?	
	PRE-PASTONIAN/PASTONIAN	WEST RUNTON (CRAG) EAST RUNTON (CRAG)		WESTBURY-SUB-MENDIP (BED 1) ?
Middle Pleistocene	CROMERIAN	WEST RUNTON SUGWORTH ? OSTEND		
	UN-NAMED INTERGLACIAL	OSTEND ?	KENT'S CAVERNS (B1)	WESTBURY-SUB-MENDIP (BEDS 2-10)
	UN-NAMED INTERGLACIAL ?	INGRESS VALE CLACTON SWANSCOMBE (LOWER LOAM)		
	HOXNIAN	HOXNE		
	UN-NAMED CONTINENTAL/ STEPPE PERIOD ?	SWANSCOMBE (UPPER MIDDLE GRAVEL) CRAYFORD	PONTNEWYDD (TYPE I) PONTNEWYDD (TYPE II) TORNEWTON (GLUTTON STRATUM)	BANWELL BONE CAVE HUTTON CAVE CLEVEDON CAVE BLEADON CAVE
	UN-NAMED 'COOL' INTER-GLACIAL	AVELEY HARKSTED STUTTON		
	UN-NAMED 'COLD' PERIOD	MARSWORTH (LOWER CHANNEL) ? STOKE TUNNEL ?		

TABLE 6.11 (continued)

	Pleistocene Stage Name/Period Type	UK Open Sites (excluding the Mendip Region)	UK cave Sites (excluding the Mendip Region)	Mendip Region Sites
Upper Pleistocene	IPSWICHIAN (Ip 3) COMPLEX INTERGLACIAL	BOBBITSHOLE SOWERBY SELSEY	VICTORIA CAVE BACON HOLE (SANDY CAVE EARTH)	MILTON HILL DURDHAM DOWN
	IPSWICHIAN (Ip 2) COMPLEX INTERGLACIAL	BARRINGTON TRAFALGAR SQUARE MARSWORTH (UPPER CHANNEL)	TORNEWTON (HYAENA STRATUM) KIRKDALE CAVE JOINT MITNOR	
	IPSWICHIAN (Ip 1) COMPLEX INTERGLACIAL	ILFORD ? SWANTON MORLEY ?	BACON HOLE (UPPER CAVE EARTH) MINCHIN HOLE	
	MID DEVENSIAN (LARGE MAMMAL FAUNAS)	UPTON WARREN TATTERSHALL CASTLE KIRKBY WRETTON ISLEWORTH COSTON BECKFORD	TORNEWTON (ELK STRATUM) KENT'S CAVERNS ELDERBUSH CAVE (LAYER 7 & 9)	PICKEN'S HOLE (LAYERS 3&5) BADGER HOLE HYAENA DEN SANDFORD HILL UPHILL (7 & 9) SOLDIERS HOLE (LAYER 4) LOXBROOK ?
	MID DEVENSIAN (ARCTIC FAUNA)		TORNEWTON (REINDEER BEAR STRATUM) PONTNEWYDD (TYPE 3) ELDERBUSH (LAYER 10)	
	LATE GLACIAL (POST DIMLINGTON STADIAL)		INCHNADAMPF (BED 3) OSSOMS CAVE (BEDS D AND C) KINSEY CAVE	GOUGH'S CAVE AVELINES HOLE CHELMS COOMBE SOLDIERS HOLE (LAYER 3) BANWELL OCHRE MINES ROWBERROW CAVERN (CEMENTED FLOOR) SUN HOLE (UNIT 1) BRIDGED POT

CHAPTER VII

PALAEOECOLOGY OF THE MENDIP REGION PLEISTOCENE VERTEBRATE FAUNAS

Seven broad Pleistocene faunal groupings have been discriminated by the multivariate analysis in Chapter VI. This number is a gross underestimate of the true range of faunal changes that have occurred in the Mendip region since the Lower Pleistocene. However, the quality of the available data does not warrant any further sub-divisions.

A number of these faunas have been recognised in the past and their palaeoecology has been discussed: most notably the Westbury-sub-Mendip faunas are known from the work of Bishop (1975,1982) and from the extensive work of the British Museum (Natural History) team led by Dr P. Andrews, whose results are to be published shortly. The Westbury-sub-Mendip faunas will therefore not be discussed.

Some aspects of the palaeoecology of the Mendip Mid-Devensian faunas have been discussed by Tratman (1968), Savage (1969), Campbell (1977) and Stuart (1983); likewise the late glacial faunas have received attention from Grigson (1978), Jacobi (1982) and Stuart (1983). However all these studies are either limited in scope or are seriously flawed. Therefore it is necessary to re-examine these faunas in the light of modern palaeoecological research.

The Mendip Region Mid Devensian Vertebrate Faunas

The greatest number of Mendip region faunal sites are characterised by large herbivores and carnivore species that are thought to be indicative of a post-Ipswichian but pre-Dimlington stadial age. The species present at eight of the Mendip region sites which are probably the least likely to have suffered gross contamination are shown in Table 7.1 and the radiocarbon dating evidence from some of these faunas is shown in Table 7.2. The radiocarbon evidence generally supports the results of the multivariate analysis that these sites are clustered (Chapter VI); they also highlight the problems of contamination and resolution of the fossil material at these sites (see Chapter V). The Badger Hole fauna has obviously been contaminated by at least early Holocene and Roman human remains (possibly resulting from burial). The Pickens Hole date also indicates problems of contamination by post-Dimlington stadial Reindeer material. The apparent stratigraphic inversion of the radiocarbon dates between layers 3 and 5 is also worrying, although the overlap between the 27000^{+1850}_{-1500} BP layer 5 date and the 27540±2440 BP layer 3 date may indicate that the Pickens Hole material was rapidly deposited and is not separable with the resolution of conventional radiocarbon analysis. Mass spectrometry C^{14} dating might resolve this problem. The Soldiers Hole results show that some degree of mixing may be present (although this could be due to the excavation technique) and also the considerable length of time over which this material was deposited.

It is clear that the resolution of the mid-Devensian Mendip faunal record is extremely crude. The results from the Mendip speleothem analysis (see Section 1) indicate that at least 6 distinct warm (interstadial) periods occurred over the period probably represented by this faunal material. It is possible that each of the warm and intervening cold periods had distinct faunas which have been amalgamated into the single fauna shown in Table 7.1.

Attempts have been made to further sub-divide this mid-Devensian fauna which is known from many UK sites. Rackman (1978) has argued that the differences in the relative proportions of the large herbivore species present at Tattershall Castle and Tattershall Thorpe in Lincolnshire are indicative of post Upton Warren faunal

TABLE 7.1 : MENDIP VERTEBRATE FAUNAS OF MID-DEVENSIAN AGE.
(Sp. denotes species. A ? denotes that the find is thought questionable by the original excavator.)
Data from Atkinson *et al* (1984), Balch (1947), Bramwell (1960), Campbell (1970,1977), Donovan (1951), Harrison (1977), Parry (1929), Stuart (1982), Tratman *et al* (1971), Turner (1981).

SITE:		Pickens Hole (Layer 5)	Pickens Hole (Layer 3)	Hyaena Den	Badger Hole	Uphill 7 + 8	Soldiers Hole (Layer 4)	Sandford Hill	Lox Brook
SPECIES									
Man (A=Artifacts, B=Bones)	*Homo sapiens*		B,A	A	B?,A	A	A		
Mountain Hare	*Lepus timidus*						+		
Susliks	*Spermophilus sp.*		+						
Arctic Lemming	*Dicrostonyx torquatus*				+		+		
Norway Lemming	*Lemmus lemmus*					+			
Northern Vole	*Microtus oeconomus*	+	+						
Tundra Vole	*Microtus gregalis*	+			+		+		
Water Vole	*Arvicola terrestris*						+		
Wolf	*Canis lupus*	+		+			+	+	
Arctic Fox	*Alopex lagopus*		+						
Red Fox	*Vulpes vulpes*	+		+?	+Sp.	+	+		
Brown Bear	*Ursus arctos*	+	+		+	+		+	
Cave Bear	*Ursus spelaeus*			+					
Spotted Hyaena	*Crocuta crocuta*		+	+	+	+	+	+	
Lion	*Panthera leo*		+	+		+	+	+	+
Mammoth	*Mammuthus primigenius*		+	+	+	+	+		+
Horse	*Equus ferus*		+	+	+	+	+	+	
Woolly Rhino	*Coelodonta antiquitatis*		+	+	+	+		+	+
Giant Irish Elk	*Megaceros giganteus*			+	+	+?	+		+
Red Deer	*Cervus elaphus*	+	+	+		+?	+		
Reindeer	*Rangifer tarandus*	+	+	+	+	+	+	+	+
Steppe Bison	*Bison priscus*	+	+Sp.	+	+	+	+	+	+Sp.
Wild Cat	*Felis sylvestris*				+				
Badger	*Meles meles*			+?					
Steppe Rhino	*Dicerorhinus hemitoechus*			+?					
Otter	*Lutra lutra*				+				
Teal	*Anas crella*						+		
Greylag Goose	*Anser anser*						+		
Lesser White Fronted Goose	*Anser erythopus*						+		
Whooper Swan	*Cygnus cygnus*						+		
Ptarmigan	*Lagopus mutus*						+		
Red Grouse	*Lagopus lagopus*						+		
Black Grouse	*Lynurus tetrix*						+		

TABLE 7.2: RADIO CARBON DATING RESULTS FROM MID DEVENSIAN VERTEBRATES IN THE MENDIP REGION. (Dates from Burleigh 1986)

SITE	MATERIAL DATED	RADIOCARBON DATE	LAB No.
Badger Hole	Bone fragments	718000 BP	BM-497
Badger Hole	Human	9060±130 BP	OXA-967
Badger Hole	Human	1380±70 BP	OXA-680
Pickens Hole (Layer 5)	Bone fragments	27000^{+1850}_{-1500} BP	BM-655B
" " "	" "	26650^{+1700}_{-1400} BP	BM-655A
" " "	Reindeer	12400±1500 BP	BM-2118
Pickens Hole (Layer 3)	Bone fragments	34265^{+2600}_{-1980} BP	BM-654
" " "	Large mammal	27540±2440 BP	BM-2117
Sandford Hill	Spotted Hyaena	36000±1900 BP	BM-1526
Soldiers Hole (layer 4, spit 12)	Reindeer	>34500 BP	OXA-691
Soldiers Hole (layer 4, spit 13)	"	29300±1100 BP	OXA-692
Soldiers Hole (layer 4, spit 14)	"	>35000 BP	OXA-693
Soldiers Hole (layer 4, spit 16)	Bovid	19300±400 BP	OXA-694

changes. However, Boyle (1983) has argued that these faunal changes can be equally well explained as resulting from taphonomic processes as by climatic fluctuations.

The palaeoecological reconstruction from the Mendip mid-Devensian faunal record (which is effectively identical to mid-Devensian faunas from other UK sites) may represent a description of the average climatic conditions that prevailed when vertebrates were present during the mid-Devensian.

The Bird Fauna

The seven species of bird identified from Soldiers Hole (layer 4) all have specific present day ecological requirements. The Teal *(Anas crecca)* favours rushy moorlands and heath pools, bogs and peat marshes. It always nests in thick cover, avoiding open habitats (Sharrock 1977).

Goose migration patterns are highly sensitive to climatic variables and have provided information on environmental conditions during both the Holocene and the Pleistocene (Ball 1983, Sutherland 1984). The Lesser White Fronted Goose *(Anser erythopys)* breeds in a narrow arctic zone in shrubs on the forest tundra edge; it favours rocky slopes along streams (Harrison 1982). During the Devensian, breeding populations were resident in southern Britain (Sutherland 1984). The Greylag Goose *(Anser anser)* is the only indigenous British Goose, nesting as far south as the Cambridge fens before the 19th Century drainage. In Scotland it favours lakes in hilly heather moorland or herb rich grasslands, where it nests in tall vegetation.

The Whooper Swan *(Cygnus cygnus)* usually breeds in sub-arctic and boreal regions. It has on occasion bred in the Orkney Isles, Scotland, around undisturbed lakes, ponds or small swamp pools surrounded by heath or moorland. (Harrison 1982, Sharrock 1977).

The Ptarmigan *(Lagopus mutus)* and Red Grouse *(Lagopus lagopus)* are confined to heather moorlands and grasslands in Scotland. They both feed on heather, crowberries and bilberries, the heather quality being particularly important to the Red Grouse. The Ptarmigan lays by the end of May at the latest, after the snow has cleared. Snowstorms or cold, wet June days cause high chick mortality. (Sharrock 1977)

The Black Grouse *(Lyrurus tetrix)* is a bird of heather moorland with trees or scrub. It is also found in pine or birch woodlands. Its optimum habitat is the forest-moorland interface with mosaic environments. Like the Ptarmigan and Red Grouse it feeds predominantly on heather. (Sharrock 1977)

To summarise, the bird fauna provides consistent evidence for a summer environment cooler than present, with unfrozen lakes or pools surrounded by some woodland, or at very least tall, dense scrub vegetation. Areas of grassland and heather moorland, probably with crowberry and bilberry, were present, possibly as a mosaic of vegetation types. Snow had probably cleared by May and good quality heather growth was available.

Bramwell (1984) has found evidence for scrub or woodland vegetation during the mid-Devensian from his analysis of the bird fauna at Pin Hole cave in Derbyshire. However these results are at direct variance with the assessment of vegetation types made by palaeobotanists for the post Upton Warren stadial. For example, Pennington (1974) describes Britain as being an *"open grass-sedge tundra"*, and Lowe & Walker (1984) *"a barren tundra landscape gradually approaching polar desert"*. Soldiers Hole was excavated during the 1920s and layer 4 is overlain by fossiliferous deposits of late glacial to recent age. From Parry's (1929) description of the excavation gross contamination seems unlikely; however any cave excavation carried out before the advent of modern techniques should be treated with some degree of caution (Stuart 1983). It is therefore necessary to look carefully at the mammal evidence from the other sites to see if it supports the reconstruction based on the bird fauna.

The Large Herbivores

The Woolly Mammoth *(Mammuthus primigenius)* became extinct in Europe around 11000 years ago, but it was one of the most successful Devensian animals, ranging across the entire Eurasian continent as far south as China (Liu Tung-shen and Li Xing-guo 1984), and into North America (Agenbroad 1984). The size of Mammoths changed during the Devensian, the largest generally being found around 32000-38000 bp during the mid-Devensian (Heintz & Garutt 1965). These stood approximately 3 metres high at shoulder height, which is a similar size to the modern Asiatic Elephant *(Elaphus maximus)* which requires 150-200 kg of food per day (Shoshani & Eisenberg 1982). Mammoth teeth have high crowns (hyposodonty) and dense packed laminae which are adaptations to grass feeding; and analysis of Siberian Mammoth stomach contents has shown the predominant presence of grasses, sedges and boreal meadow and tundra plants (Heintz 1958). However, twigs, cones and the pollen of 11 species of trees and shrubs were also found, including fir, larch, alder, birch, spruce, pine and willow (Heintz 1958, Farrand 1961). Mammoth remains from Eschscholtz Bay in Alaska have also been found in association with *"large trees"*, among them spruce, fir and alder (Quackenbush 1909). These areas are now treeless but probably had milder and wetter climates than at present when the mammoths inhabited them.

Oliver (1982) has argued that Mammoths were highly adapted grazers able to subsist upon a high fibre/low protein nutritionally poor diet of grasses by eating large quantities. However, the caecal fermentation of Mammoths (and modern Elephants) that allowed this large throughput of food means that substantial quantities of complex amino acids would not have been microbial produced within the Mammoths' digestive tract. Therefore, in order to supplement their staple diet of nutritionally poor grasses, Mammoths, like modern Elephants, would have required browse from woody species to optimise amino acid balances, maintain balances of essential cations (such as Ca^{+} and Na^{+} and obtain the essential fatty acids needed for milk production (Oliver 1982). The biological necessity of browse to optimize the Mammoths' diet would have been particularly critical in winter months when grasses are generally extremely nutrient-poor. Therefore, in winter, woody cover would have been necessary for Mammoth survival. *"It seems unlikely that even tussocky ground would provide sufficient forage"* (Oliver, quoted in Stanley 1980). These biological limitations apply equally to all large herbivores with caecal digestion such as the Woolly Rhino.

The Horse *(Equus ferus)* is highly adaptable, surviving in all types of environment except marshes and deep snow. Russian Horses exhibit extreme cold tolerance, surviving in temperatures as low as -50C with up to 50-70 cm of snow. Horses are specialized grazers capable of surviving on the coarsest, most fibrous vegetation, with a lower protein content than virtually any other large herbivore (Jannis 1976).

The Woolly Rhino *(Coelodonta antiquitatis)*, like the mammoth, was an extremely successful Devensian animal, ranging throughout Eurasia, although for some reason it never managed to cross the Beringian land bridge into North America (Kurten 1968). It is commonly stated that the Woolly Rhino was an extreme tundra form. For example, Kurten (1968) writes *"not only the head but also the neck was carried low in this species; thus showing extreme grass eating specialization"*. However, the available data does not support this view. The most characteristic adaptation of grazing herbivores is a head angle that places their mouth close to the ground - the most important single measure being the angle between the Opsithma + Basion and the Parietals (Loose 1975). As can be seen from Table 7.3 , the Woolly Rhino has a similar angle to *Dicerorhinus sumatrensis* and *Dicerorhinus bicornis*: both these species are exclusively browsing animals, stooping to graze only when browse is insufficient (Groves & Kurt 1972, Loose 1975). *Ceratotherium simum*, by contrast, has a much higher angle (110°) and is exclusively a grazer. Supplementary

TABLE 7.3 : COMPARISON OF THE ANGLE IN DEGREES BETWEEN THE OPISTHION + BASION AND PARIETALS IN EXTINCT PLEISTOCENE RHINOS AND THE MODERN TWO HORNED RHINOS.

	(Zeuner 1934)			(Loose 1975)		
Species	median	range	no.	median	range	no.
D. sumatrensis	95	88-100	5	97	87-107	12
D. bicornis	90	74-120	42	89	72-100	25
C. simum	110,5	89-131	8	109	95-113	10
C. antiquitatis (Woolly Rhino)				94,5	82-102	8
D. etruscus	98,5	80-107	6	93	88-104	7
D. kirchbergensis	95,5	82-109	4	97	93-107	4
D. hemitoechus				118	110-120	7

evidence for browsing in the Woolly Rhino comes from the discovery that the specimens preserved in salt and petroleum at Starunia, Poland, had conifer needles between their teeth (Nowak *et al* 1930).

The Giant Irish Elk *(Megaceros giganteus)* had become extinct by 10000 bp, but it was a successful Devensian animal ranging throughout most of Eurasia down as far as North Africa (Coope 1973). An ecological interpretation of its cranial morphology is outstanding. However, it must have inhabited fairly open terrain since the males had huge antlers with up to 4 metres spread (Gould 1975).

Reindeer *(Rangifer tarandus)* presently occur in three types of habitats: fells, tundra and taiga forests. The tundra (barren ground) ecotype live in huge herds (>2000) and migrate in winter, sometimes long distances, to the tundra-forest edge. The fell and taiga (woodland ecotype) Reindeer tend to only migrate short distances, if at all (Smit & Wijngaarden 1976). Male Reindeer cast their antlers from November to February, following the October rut. Female Reindeer cast antlers in April or May. Since cast antlers of both male and female Reindeer are present at Sandford Hill and Hyaena Den, they were undoubtedly present on Mendip during spring and late autumn/early winter, and possibly throughout the entire year (Stuart 1982, Turner 1977).

The Red Deer *(Cervus elaphus)* is found in a wide range of habitats, from forest to desert scrubland, where they prefer the transition zone between forest and savannah. In continental Europe Red Deer are always associated with woodland habitats; however in Scotland they have adapted to open moorland and upland grasslands (Mitchell *et al* 1977). In woodland, browse from trees and shrubs forms between 45%-80% of the food selected, depending on the woodland type (Dzieciolowski 1970). In Scotland grasses can form up to 90% of the diet in summer, although in winter browse from shrubs (particularly heather) is important to survival (Mitchell *et al* 1977). The northern limit of Red Deer in Eurasia is generally thought to be set by snowfall. They do not occur further north than where the average yearly maximum snow depth is 40-50 cm. They are only found in large numbers where snow cover does not exceed 20-30 cm (Formozov (1946) quoted in Mitchell *et al* 1977).

The Steppe Bison *(Bison priscus)* was a common Devensian animal in Eurasia, which became extinct by the late Devensian (Stuart 1982). Detailed palaeoecological interpretations of its skull morphology do not exist; however Geist (1971) has reconstructed the appearance of *Bison priscus* based on 41 reproductions left in central Europe during the Würm, by the Aurignacian and Magdalenian cultures. The head position shows the nose upturned like the modern browsing forest bison *(Bison bonasus)*. The modern grass eating plains bison *(Bison bison)* has its head angled so as to place its mouth close to the ground in the typical grazing position.

The principle of competitive exclusion is a fundamental tenet of ecological theory, which asserts that no two species of animal can co-exist together in the same habitat if they occupy the same niche. No-one has yet attempted to reconstruct how the impressive range of large herbivores described, managed to co-exist in mid-Devensian Britain without competitively excluding each other. A reconstruction is outside the scope of this work; however a number of details can be surmised from the previous discussion. All of these herbivores were of either equal size or larger than their present day counterparts (a fact attributed to Bergman's law by Kurten (1968) but more realistically explained by Guthrie (1984) as due to "dispersal theory"). In order to support such a diverse range of large herbivores the vegetation must have been nutritious, plentiful, lush and varied, which is a situation completely unlike present day "barren tundra landscapes" or "polar deserts". With the exception of Horse and Reindeer, all the other herbivores discussed, whose ecology is known or deduced, required woody shrubs or trees for forage during at least part of the year. This indicates that the vegetation was predominantly herb-rich grassland with areas of shrubs and/or trees.

The basal wear patterns on both Woolly Rhino horns and Mammoth tusks indicate that they were used to sweep aside snow to get at vegetation, so some snow was probably present (Fortelius 1983). However, the presence of Horse, Red Deer, Woolly Rhino, Mammoth and Bison all attest to this snow cover being only shallow (<50cm).

Axelrod (1967), Holman (1977), Guthrie (1984) and others have persuasively argued that the environment during the last glacial period was more equitable than at present, the large herbivores managing to survive because of the consequently longer growing season. Their evidence has been rejected in part by Read (1969) and is contradicted in Britain by the occurrence of periglacial features associated with marked seasonality (Williams 1975). Mammoths, Woolly Rhino, Giant Irish Elk and Steppe Bison all had massive tusks, horns and antlers (Fortelius 1983, Geist 1971, Gould 1974). Elaborate display organs are selectively advantageous in seasonal 'boom and bust' ecosystems, so that male interaction is restricted to a short 'rutting' period, which saves time for feeding during the period of super-abundance of food (Gould 1974, Pruitt 1978). Further evidence for seasonality comes from the presence of bands or growth rings in the mandibles, tooth cementum and horns of many mammals - particularly the Woolly Rhino and Mammoth. Broad bands are thought to represent rapid growth in summer and the thin bands slower winter growth (Fortelius 1983, Stuart 1982).

The Rodent Evidence

Both the Tundra Vole *(Microtus gregalis)* and the Northern Vole *(Microtus oeconomus)* are found in tundra, taiga and wooded steppe habitats. They both eat stems, leaves and roots of many species of grasses and sedges. Where they exist together the Tundra Vole is confined to the wetter habitats, where it nests in grass and sedge tussocks. The Northern Vole nests in quite extensive burrows (Stuart 1982, Smit & Wijngaarden 1976).

The Arctic Lemming *(Dicrostonyx torquatus)* and Norway Lemming *(Lemmus lemmus)* occur throughout the entire palaeoarctic tundra and into the taiga. Their diet consists of grasses and sedges in summer, with buds, twigs and willow bark being important to Arctic Lemming in winter. Neither species is capable of surviving on heathland plants (Jung and Batzli 1981); therefore the simultaneous fossil occurrence of both lemmings and heathland adapted mammal species is either indicative of a mosaic of environments or that temporally separate faunas have become intermixed. Where both species are present the Norway Lemming is confined to the wetter habitats. Both species burrow - the Norway Lemming more extensively than the Arctic Lemming (Corbet 1966).

The Carnivore Evidence

Carnivore presence is of limited use for environmental reconstruction since their distribution is predominantly controlled by the availability of suitable prey. Turner (1981) has fully described the likely predator-prey interactions on Mendip during the mid-Devensian. A limited number of useful observations can however be made if a degree of ecological stability is assumed in hunting strategies. Wolves *(Canis lupus)* and Spotted Hyaenas *(Crocuta crocuta)* hunt by following their prey, sometimes over long distances, in both open and wooded habitats. However, Lions *(Panthera leo)* and Wild Cats (*Felis sylvestris)* both hunt by stalking and therefore require some cover in which to hide (Schaller 1972). Although both species were larger during the mid-Devensian than at present (Kurten 1965, Turner 1981), there seems no reason to believe that their methods of hunting has changed. However, it must be noted that Wild Cats are normally associated with wooded habitats (Corbet & Southern 1977). The record of Wild Cat along with Otter only comes from the Badger Hole site, which the C^{14} dating results (Table 7.2) have shown to suffer from Holocene contamination. It seems possible that both Wild Cat and Otter are contaminants, and are not elements of the mid-Devensian fauna.

In Britain the Red Fox *(Vulpes vulpes)* is most abundant in fragmentary habitats offering a wide variety of cover and food (Corbet & Southern 1977), particularly habitats with an appreciable length of woodland-farmland 'edge' (MacDonald *et al* 1981). Radio tracking studies in tundra habitats in British Columbia have shown that the Red Fox strongly confines its activities to willow *(Salix sp.)* communities 1.0 - 1.5 metres high, and avoids open lichen-empetrum communities (Jones & Theberge 1982).

Discussion

The presence of mammals and birds adapted to arctic environments (eg Arctic Fox, Arctic Lemming and Lesser White Fronted Goose) strongly suggests that the mid-Devensian climate of Mendip was considerably colder than at present. However, the association of 'native' tundra species with mammals associated with non-arctic environments at present needs an explanation.

Most mammals are capable of tolerating quite extreme cold (Hardy 1979); what currently excludes them from present day arctic environments is the shortness of the growing season, necessitating the beginning of reproduction before spring. Pruitt (1978) states:

> *"It is not the severe climate, nor the character of the vegetation, nor even the presence of permafrost which limits them. The basic reason is the shortening of the summer period - a phenomenon related directly to latitude."*

Since the latitude of the Mendips has remained unchanged from the Devensian to the present, the association of the animals listed in Table 7.1 in face of extreme cold is not problematic. However, for such a diverse fauna to survive, the vegetation must not only have been nutritious and plentiful, but also considerably more diverse than is found in any present day tundra environment.

McCoy & Connor (1980) have shown that the latitudinal gradient of a number of species of quadruped mammals is primarily due to the "patchiness" of the vegetation - low latitudes containing more diverse habitats than northern climates.

These facts, plus the considerable evidence already discussed for the presence of tall, woody shrubs and/or trees, argues strongly against any direct analogy between mid-Devensian British environments and those of the present day arctic.

Mid-Devensian Mendip seems to have been covered by a diverse mosaic of plant communities, predominantly grassland but with areas of heather moorland as well as tall vegetation of woody shrub and/or trees. Although none of the evidence for tall vegetation discussed is conclusive in isolation, to argue it all away as a combination of contamination, migration, changed ecologies, etc, requires a considerable amount of special pleading.

The present day arctic tree line is controlled by a number of complex factors which differ for each species of tree (Pruitt 1978). However extensive willow thicket communities containing tree sized willows (+5 metres) occur in sheltered valleys in the middle of true tundra environments, over 650 km north of the timberline (Maycock & Matthews 1967). An important controlling factor seems to be the depth of permafrost. The much greater amount of solar insolation received on Devensian Mendip compared to the present day arctic would have presumably led to a deep active layer above any permafrost; a suggestion supported by the presence of burrowing mammals. Therefore, there seems to be no obvious reason that would have prevented willows and other hardy species from reaching tree size on mid-Devensian Mendip.

To conclude, the fossil vertebrate evidence suggests that mid-Devensian Mendip had a cold, seasonal climate. Snow had cleared by May and probably did not exceed half a metre in depth. In summer unfrozen lakes and pools existed and if permafrost was present it was at depth. There was a nutritious and plentiful diverse mosaic of plant communities, predominantly grass, but with areas of heather as well as tall vegetation of woody shrubs and possibly trees. Alternatively the heather moorland could have been confined to the acidic Old Red Sandstone core of the Mendips, with the herb rich grasslands concentrated on the base rich limestone flanks. Areas of tall scrub and/or woodland could have grown in the sheltered valleys and gorges.

The environment described in this reconstruction is clearly one which would be associated with general interstadial conditions. It is at direct variance with palaeobotanical evidence and the speleothem evidence for average mid-Devensian climatic conditions which indicate that stadial environments were more common than interstadial environments between the last interglacial and the Dimlington stadial. Therefore the idea that the mid-Devensian faunas will represent some kind of average environment for this period is clearly wrong. A possible explanation of this discrepancy is that the classic large mammal Devensian faunas are predominantly interstadial faunas, the intervening stadials being characterised by a sparse and restricted fauna comprised of extremely hardy species such as Reindeer and Musk Ox. Alternatively the majority of the faunal elements could have been present only in the summer months, migrating southward en masse during winter. However, the available evidence from the seasonal indicators runs contrary to this hypothesis and the sedentary nature of some of the faunal elements also mitigates against it.

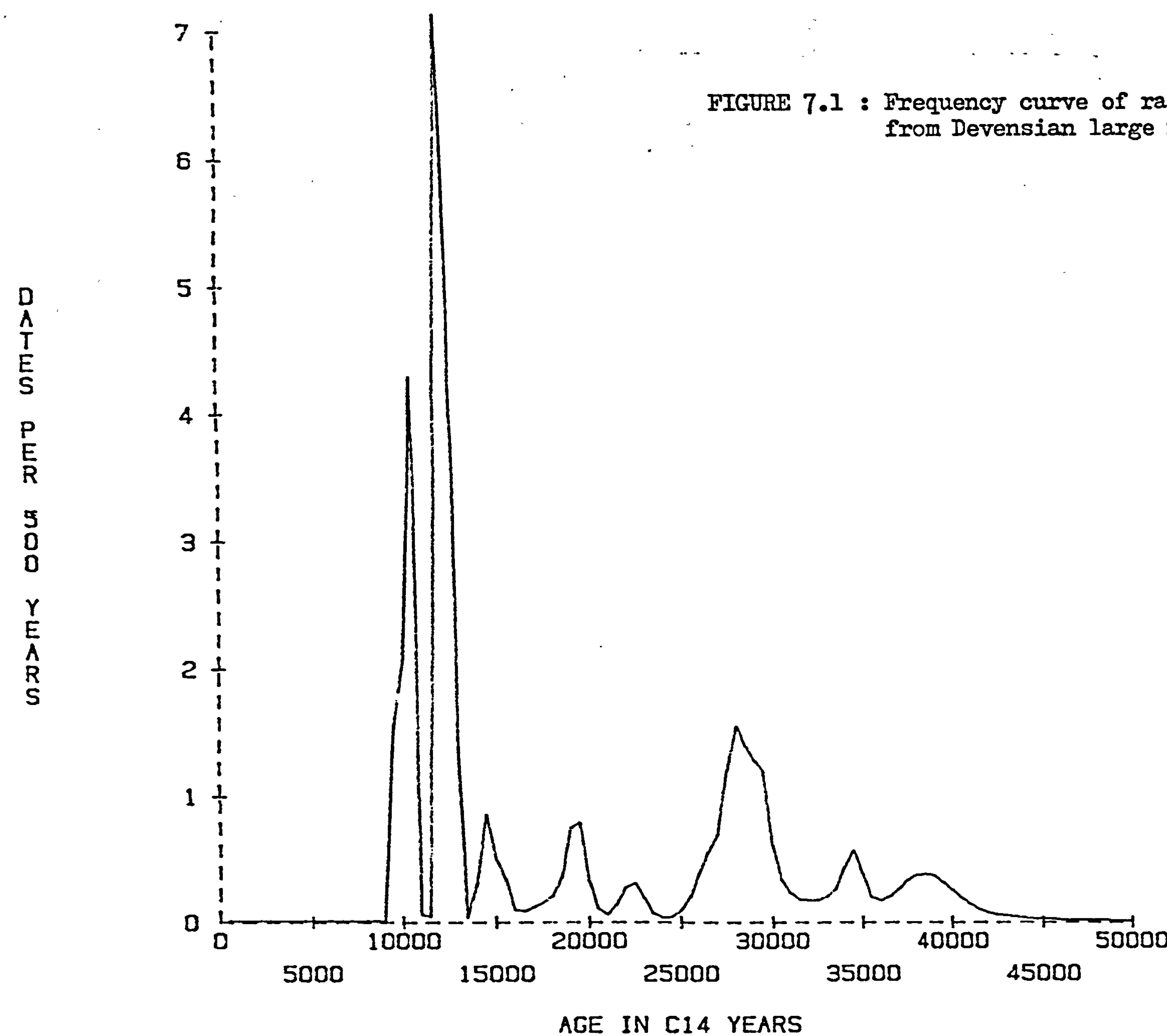
It should be possible to discriminate between these two hypotheses using the radiocarbon dating evidence. If the faunas were predominantly present during interstadials then the C^{14} dates will be clumped within these periods. If however the faunas were present during the summer months throughout the Devensian, the C^{14} dates will be more randomly distributed. A modified version of the distributed error weighted frequency curve technique (similar to that of Berendsen 1984) was used to analyse the C^{14} data from Pleistocene large mammal remains (Figure 7.1)

Unfortunately the number of available dates is too small (43) to yield reliable results. However the results shown in Figure 7.1 indicate that the C^{14} dates are probably clumped into distinct periods. If this is correct and not a statistical or C^{14} production artifact then it may be possible to calibrate the C^{14} timescale to the uranium-series speleothem growth record as large mammals are most likely to have been present during the warm vegetated conditions that favour speleothem growth. When more C^{14} dates are available it will become possible to test this idea.

The Late Glacial Faunas

The second most abundant grouping of faunal sites can be assigned a broad post-Dimlington stadial, but pre-Holocene age. These faunas are characterised by lacking the typical large mammals of the mid-Devensian sites while retaining a number of characteristic arctic and steppe species, particularly the steppe pika. Although these characteristic faunas have been recognised since the early 1960s they have not been described as being explicitly late glacial until recently, eg Jacobi (1982) and Stuart (1983). However both these studies are seriously flawed in that the species lists they present are not those described by the original investigators. Many elements indicative of non-steppe and non-tundra conditions have been selectively removed from the species lists. The dangers of this approach in leading to tautological arguments have already been discussed (Chapter V). Currant (1986) has also argued against this kind of *"ecological sifting"* as it *"tends to harden the artificial boundaries we like to create between successive climatic phases in the Quaternary, yet the late glacial period had such a wide variety of climatic events in so short a period that all environments were*

FIGURE 7.1 : Frequency curve of radiocarbon dates from Devensian large mammal bones.



arguably transitional....within any one unit on a late glacial sequence, apparent faunal mixing may be the rule rather than the exception."

The Bird faunas from the Mendip region sites are shown in Table 7.4. All these faunas are probably late glacial in age except for that from Soldiers Hole, layer 4, which is included for comparison. The mammal faunas from eight late-glacial Mendip region sites that are least likely to be seriously contaminated are shown in Table 7.5. A number of the species are common to both the late-glacial and mid-Devensian faunas and their likely palaeoecological requirements have already been discussed.

The Bird Faunas

The bird species listed in Table 7.4 have been assigned to five ecological preference categories:

(1) Aquatic (A)

(2) Grassland and Open Country (G)

(3) Scrubland, Parkland and Edge of Woodland (S)

(4) Woodland (W)

(5) Other, predominantly rock nesters and marine birds (O)

These categories should not be considered as fixed but relate to the type of environments that these species predominantly inhabit and/or prefer at present. They are based upon the ecological descriptions given in Sharrock (1977) and Lack (1986) and are probably highly reliable. Sharrock (1977) is compiled from the observations of between 10000-15000 bird watchers between 1968 and 1972, and Lack (1986) from the observations of about 10000 bird watchers during 1981 to 1984. The ecological preferences of these bird faunas are displayed as percentage histograms in Figure 7.2 . There are probably taphonomic differences between these sites. This is most clearly displayed by the aquatic elements which are present at Soldiers Hole and Gough's Cave but absent from Aveline's Hole and Chelm's Coombe. There seems no reason to believe that this is due to environmental differences.

TABLE 7.4 : BIRD FAUNAS FROM MENDIP REGION SITES

Common Name	Latin Name	Averline's Hole 0-30cm	Averline's Hole 30-60cm	Averline's Hole 6-,90cm	Soldiers Hole Layer 2	Soldiers Hole Layer 3	Soldiers Hole Layer 4	Chelms Coombe	Goughs Cave Pleistocene Levels	Environmental Preference
Barnacle Goose	*Branta leucopis*							+		O
Greylag Goose	*Anser anser*				+		+		+	A
Lesser White Fronted Goose	*Anser erytaropus*						+			A
Whooper Swan	*Cygnus cygnus*						+		+	A
Mallard	*Anas platyrhynchos*				+	+				A
Teal	*Anas crecca*					+	+			A
Golden Eagle	*Aquila chrysaetos*	+			+					O
Peregrine Falcon	*Falco peregrinus*	+	+						+	O
Kestrel	*Falco tinnunculus*		+	+	+			+		O
Red Grouse	*Largopus largopus*	+	+	+		+	+	+	+	G
Ptarmigan	*Largopus mutus*	+	+		+	+	+	+	+	G
Black Grouse	*Tertrad tetrix*				+	+	+			S
Partridge	*Perdix perdix*	+	+	+		+		+		G
Moor Hen	*Gallinula chloropus*					+				A
Lapwing	*Vanellus vanellus*	+								G
Golden Plover	*Pluvialis apricaria*	+								G
Grey Plover	*Pluvialis squatarola*		+							G
Curlew	*Numenius arquata*	+	+							G
Herring Gull	*Largus argentatus*		+							O
Common Gull	*Larus canus*					+				O
Black Tailed Godwit	*Limosa limosa*					+				G
Stock/Rock Doves	*Columba oenas*	+				+			+	S
Eagle Owl	*Bubo bubo*							+		O
Little Owl	*Athene noctua*			+						S
Short Eared Owl	*Asio flammeus*	+				+				G
Green Woodpecker	*Picus viridis*							+		S
Skylark	*Alauda arvensis*	+	+							G
Swallow	*Hirundo rustica*	+	+	+						O
Raven	*Corvus corax*					+				G
Rook	*Corvus frugilegus*		+							S
Jackdaw	*Corvus monedula*	+				+				S
Magpie	*Pica pica*			+		+				S
Jay	*Garrulus glandarius*					+				W
Great Tit	*Parus major*	+	+	+				+		W
Nuthatch	*Sitta europaea*	+	+							W
Mistle Thrush	*Turdus viscivorus*	+	+	+		+		+		S
Field Fare	*Turdus pilaris*	+	+	+		+			+	G
Song Thrush	*Turdus philomelos*	+	+	+				+		S
Redwing	*Turdus iliacus*			+				+		S
Ring Ouzel	*Turdus torquatus*					+		+	+	G
Blackbird	*Turdus merule*	+	+	+				+	+	S
Whinchat	*Saxicola rubetra*	+	+							G

(continued)

Common Name	Latin Name	Averline's Hole 0,30cm	Averline's Hole 30-60cm	Averline's Hole 60,90cm	Soldiers Hole Layer 2	Soldiers Hole Layer 3	Soldiers Hole Layer 4	Chelms Coombe	Goughs Cave Pleistocene Levels	Environmental Preference
Red Start	*Phoenicurus phoenicurus*	+	+							S
Robin	*Erithacus rubecula*	+								W
Black Cap	*Sylvia atricapilla*			+						W
Pied Wagtail	*Motacilla alba*			+				+		O
Hawfinch	*Coccothraustes coccothrustes*	+	+							W
Green Finch	*Carduelis chloris*							+		S
Linnet	*Carduelis cannabina*			+						G
Bullfinch	*Pyrrhula pyrrhula*	+								S
Chaffinch	*Fringilla coelebs*	+								W
Corn Bunting	*Miliaria calandra*			+						G
Yellow Hammer	*Emberiza citrinella*	+								G
Snow Bunting	*Plectrophenax nivalis*	+								G
House Sparrow	*Passer domesticus*	+		+						O
Meadow Pipit	*Anthus pratenis*	+	+					+		G
Little Auk	*Alle alle*							+		O

TABLE 7.5 : LATE GLACIAL MAMMAL FAUNAL SITES IN THE MENDIP REGION

SITES:	Aveline's Hole	Chelm's Coombe	Bridged Pot Ebbor	Sunhole Unit 1	Gough's Cave	Soldiers Hole Layer 3	Banwell Ochre Mines	Rowberrow Cavern Cemented Floor
Common Shrew	+							+
Mole		+		+				
Whiskered Bat	+							
Beckstein's Bat	+							
Man	+	+	+	+	+	+		
Arctic Hare	+	+	+	+	+	+	+	
Steppe Pika	+	+	+	+	+	+	+	+
Beaver				+	+			
Arctic Lemming	+	+	+	+		+		+
Norway Lemming	+			+	+			
Bank Vole	+			+				
Water Vole	+	+	+	+	+	+	+	
Common Vole	+	+	+	+		+		
Field Vole	+	+	+					
Northern Vole	+	+	+	+			+	
Tundra Vole	+	+	+	+		+		
Wood Mouse	+	+		+				+
Wolf	+		+	+	+			+
Arctic Fox		+	+		+			
Red Fox	+	+	+	+	+	+		
Brown Bear	+		+	+	+			
Badger	+							
Stoat		+						
Weasel			+	+				
Polecat	+							
Wolverine		+						
Wild Cat				+				
Lynx	+							
Horse	+	+	+	+	+			+
Wild Boar	+	+						
Red Deer	+	+			+			+
Roe Deer			+					
Giant Deer			+					
Reindeer	+	+	+	+	+	+		+
Bison	+					+		
Aurochs					+			
Saiga Antelope				+	+			

FIGURE 7.2 : Percentage histograms of the ecological preferences of Mendip region fossil bird faunas. (A = Aquatic, G = Grassland and open country, S = Scrubland, parkland and woodland edge, W = Woodland, O = Other.)

All the late glacial bird faunas contain a significant proportion of woodland and/or scrubland species, and it would seem highly unlikely that they could all result from Holocene contamination, particularly since this result is consistent with the work of Bramwell (1960,1986) who found a significant woodland element in the late glacial bird faunas from Robinhood and Pin Hole caves in Derbyshire. The true woodland element is represented by seven species. These are: Jay, Nuthatch, Great Tit, Robin, Hawfinch, Chaffinch and Blackcap. All these species are commonly associated with mature trees, although some can be found nesting in hedgerows. However these are markedly sub-optimal habitats: hedgerow-nesting Robin populations have been shown to suffer high mortality rates during severe winters (Williamson 1972). Nor does it seem likely that these birds were just summer visitors: the Nuthatch in particular has an extremely sedentary nature, establishing and defending territories throughout autumn and winter (Nilsson 1976, Enokisson & Nilsson 1983). Although these seven bird species require mature trees, they, along with the scrubland species, would probably all be able to survive in a birch forest habitat and many can be found today in Scandinavian birch forests (Lack 1986). This interpretation is consistent with the pollen evidence for Windermere interstadial birch forest in the UK (Godwin 1975) and with the pollen analysis from Gough's cave sediments which contained birch tree pollen (Leroi-Gourhan 1985).

The habitat requirements of the grassland/open country species are in marked contrast to the woodland species. Birds like the Golden Plover, Curlew, Black Tailed Godwit, Lapwing, Skylark, etc., are all confined to open habitats. For example, the Black Tailed Godwits breed only in damp undulating meadows, moorland or blanket bogs. Their habitat preference is so specific they currently breed in only 20 to 30 sites in the British Isles (Sharrock 1976). It seems unlikely that these contradictory environmental requirements could be provided by a single habitat or mosaic of habitats. A mutual climatic range study on the bird faunas similar to that of Atkinson *et al* (1987) on Beetles might resolve this problem but it seems more likely that the late glacial fauna is composite with significant interstadial and stadial faunas intermixed.

The Mammal Fauna

Like the bird fauna the late glacial mammal fauna (Table 7.5 is confusing, containing species with mutually exclusive climatic requirements. A significant woodland element is present (eg Lynx, Wolverine, Beaver, Wild Boar, Wild Cat, Wood Mouse, etc) along with a relatively thermophilous element (eg Mole, Whiskered Bat, Beckstein's Bat). These contrast strongly with the Arctic and Steppe elements such as Arctic Fox, Reindeer and Saiga Antelope. For example, the Saiga Antelope currently only inhabits a narrow steppe zone in central Russia (Bannikov 1961). It is an animal adapted to flat grasslands with arid climates (dry steppes and semi deserts) avoiding any snow patches even if this means taking long detours (Sokolov 1974). The presence of Saiga Antelopes can be taken to be indicative of less than 20cm of snow (Harrington 1980). It is difficult to reconcile the occurrence of Saiga and Reindeer (an animal adapted to deep snow) let alone the simultaneous presence of Beaver. However it is unlikely that all the woodland and thermophilous elements are Holocene contamination (Colcutt *et al* 1981), therefore several different late glacial faunas each with a significant number of species may be intermixed. This interpretation is consistent with the cluster analysis results. It may prove possible to separate these distinct faunas by Mass Spectrometry C^{14} dating and progress towards this has already been made with the Gough's cave assemblage (see Chapter VI and Currant 1986). At least two faunas are present, although there are probably more than this.

The 'Last Interglacial' Faunas

The Upper Pleistocene interglacial faunas from the Mendip region are represented from just two sites: Milton Hill and Durdham Down. The faunas from these sites are shown in Table 7.6 and have relatively few species in common. Which of the three Upper Pleistocene interglacials these faunas belong to is unknown, although the cluster analysis results (Chapter VI) are consistent with an Ip 3 age (125000 years BP). All the species present are known from other UK Upper Pleistocene interglacial sites with the exception of Reindeer (Stuart 1974,1976). The lack of any small mammal remains is undoubtedly due to the excavation techniques used and the presence of Reindeer could well be due to either misidentification or the intermixing of museum samples. The faunas are typical of deciduous woodlands with thermophilous conditions. For example, Roe Deer prefer woodland habitats with plenty of cover (Whitehead 1964, Batchelor 1960) and browse from trees is particularly important for winter survival (Suida *et al* 1969, Table 7.7). Despite the small importance of grasses for Roe Deer, there is faunal evidence for substantial amounts of grassland. The extinct Rhino *Dicerorhinus hemitoechus* has the characteristics of a specialist grazer. The angle between the opisthium and basion and parietals is similar to that of the modern grazing Rhino Ceratotherium simium (Table 7.3) - both species have sturdy symphysis of the mandible indicative of relatively great activity. However, the teeth of *D.hemitoechus* are large but not as large as *C.simum* which may indicate that the interglacial grasses were less abrasive than modern tropical grasses (Loose 1975). *D.hemitoechus* appears to be the only Pleistocene Rhino specifically adapted to grazing (Loose 1975).

The two faunas as a whole are indicative of a mosaic of habitats with mature open deciduous and/or mixed woodland, areas of open plains or grassland and reasonably sized rivers. They are temperate faunas with no indication of continental or arctic conditions (if the records of Reindeer are excluded).

TABLE 7.6 : 'LAST INTERGLACIAL COMPLEX' MAMMAL FAUNAL SITES FROM THE MENDIP REGION

		Milton Hill	Durdham Down
Canis lupus	Wolf		+
Vulpes vulpes	Red Fox		+
Ursus arctos	Brown Bear		+
Ursus spelalus	Cave Bear		+
Meles meles	Badger		+
Lutra lutra	Otter		+
Crocuta crocuta	Spotted Hyaena	+	+
Panthera leo	Lion		+
Palaeoloxodon antiquus	Straight Tusked Elephant	+	+
Mammuthus primigenius	Mammoth		+
Equus ferus	Horse		+
Dicerorhinus hemitoechus	Extinct Rhino		+
Hippopotamus amphibius	Hippo	+	+
Cervus elaphus	Red Deer	+	
Capreolus capreolus	Roe Deer	+	
Megaceros giganteus	Giant Deer	+	
Rangifer tarandus	Reindeer	+	+
Bison priscus	Bison	+	
Bos primigenius	Aurochs	+	

Table 7.7: PERCENTAGE OF PLANT GROUPS IN ROE DEER RUMENS (STOMACHS) AT DIFFERENT SEASONS OF THE YEAR (adapted from Suida *et al* 1969)

Season:	Spring	Summer	Autumn	Winter
Number of Rumens examined	9	9	7	21
Trees	38	17	20	43
Shrubs & bushy plants	5	50	43	37
Herbs	39	15	23	11
Grasses, sedges, seeds	4	7	2	2
Lower plants & unidentified	15	11	12	7

<u>The Mid Pleistocene 'Continental/Steppe' Faunas</u>

The cluster analysis results indicate that mammalian faunas from four Mendip region sites may date from the mid-Pleistocene. They are:

1) Clevedon Cave
2) Hutton Cave
3) Banwell Bone Cave
4) Bleadon Cave (in part)

These sites have been identified on the basis of a number of 'indicator' species rather than on the complete faunas, which are generally similar to those from mid-Devensian sites. Little is known about the later half of the mid-Pleistocene in Britain and it is far from certain that all these faunas date from the same period. The likely degree of contamination and faunal mixing is unknown at all these sites, although it is probably considerable with the Bleadon Cavern faunal data (see Chapter VI). Banwell Bone Cave is one of the richest Pleistocene fossil sites in Europe, yet it has never been properly studied. Despite the interesting work of Moore (1878), Davies & Gray (1905), Hunt (1953,1954) and Sutcliffe (1955), the Banwell Bone Cave faunas are still poorly known.

Clevedon and Hutton caves were excavated during the late 19th Century and complete species lists are found in Reynolds (1907) and Balch (1947) (see Appendix 2). This fossil material has only been partially re-examined in modern times and is in need of revision before definite ecological conclusions can be drawn from these faunas. Considering these problems, an ecological reconstruction based on all the species present at these four sites would be misleading. However the ecologies of the 'indicator' species will be discussed.

The common hamster (*Cricetus cricetus*) is a characteristic mammal of the steppes and grasslands of central and eastern Europe and western Asia. It feeds predominantly on seeds and cereal grains and is adapted to carrying food in its cheek pouches which it caches in burrows for winter. Common hamsters can survive extremely severe winter conditions by hibernating in deep burrows and periodically waking to feed on its extensive food stores. They are therefore well adapted to steppes with continental climates.

The ecology of the extinct hamster *Allocricetus bursae* is unknown. However this species was smaller than common hamster (Sutcliffe & Kowalski 1976). Present day small species of the *cricetinae* are found from central Asia to the Ukraine, with isolated populations in Bulgaria and Greece. They are frequently associated with forest-steppe environments.

The leopard *(Panthera pardus)* is a highly adaptable animal with the widest present day distribution of any large predator except man (Turnbull-Kemp 1967). Although it is fast over short distances it hunts by stalking and commonly drags the carcasses up into trees to protect them from scavengers. The occurrence of leopard is therefore indicative of the presence of some large trees (Turnbull-Kemp 1967).

In conclusion, if these three species did co-exist simultaneously, then they suggest a wooded steppe environment and probably continental climatic conditions.

SECTION III

THE SEDIMENT RECORD

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Introduction

It had initially been the aim of this thesis to give a detailed account of Quaternary sedimentation in the Mendip region in the same manner as has been done for the speleothem and faunal records in the previous sections. However, such an account would be premature with our current state of knowledge for the following reasons:

The Mendip Hills are a buried fossil landform that has only been partly exhumed by scarp retreat. The major geomorphological features were formed by Triassic weathering and the landscape was then buried by Jurassic and Cretaceous marine sediments. These Mesozoic sediments were probably only stripped during the Pleistocene to expose this ancient landscape in western Mendip. Eastern Mendip still retains its Mesozoic cover. This means that much of the topography is complex and difficult to interpret as Pleistocene features have been superimposed upon Triassic landforms (Frey 1975). It is unlikely that much lower Pleistocene material has been preserved as, during this period, much of the current landscape was still overlain by soft Mesozoic rocks and few sediment traps would have been exposed.

The limestone plateau is relatively exposed and has only a thin covering of superficial deposits, except in the major depressions, the vast majority of which have never been studied. The flanks of the Mendips are generally spectacularly steep and contain few sediment traps - the majority of dry valleys having been flushed of sediment, presumably during the last glaciation. The dry valley and gorge mouths are characteristically covered in massive gravel aprons and fans of considerable thickness. The exposed sediments are almost exclusively of late and mid Devensian age and have been extensively studied by Macklin (1985). The foot of the slopes are also characterised by thick sediment deposits and are therefore difficult to study, as the first 4 metres are frequently exclusively Holocene. These slope sediments and their contained fossil Mollusca have been studied by Willing (1985). The majority of Pleistocene sediment exposures are found either in the caves or in the coastal region. Gilbertson (1974) and Gilbertson & Hawkins (1977) have constructed a number of sedimentary records from the study of the coastal lowland deposits. However these sequences are virtually devoid of any chronological control and the Quaternary stratigraphic record that they have used for their reconstructions is demonstrably incomplete (Sections 1 & 11). Therefore the dating and ordering of these sequences is open to question.

The cave record undoubtedly shows the greatest promise for the reconstruction of a Pleistocene sedimentary record, as caves often act as sediment traps during both 'warm' and 'cold' periods. Once abandoned, many caves slowly fill up with sediments until choked, and then preserve them until re-exposed by solutional lowering of the plateau surface, or by human excavation. Cave environments also buffer sediments from the extremes of climatic variation; thus preservation states are often excellent. Finally, the frequent occurrence of stratified, dateable speleothems and fossil remains potentially allows the sedimentary sequence to be tied into both an absolute chronostratigraphic framework and a biostratigraphic framework.

Therefore, caves can often act as 'sedimentary time capsules' by trapping and preserving Pleistocene sediments over an extended period. By tying together several such sequences using the speleothem and faunal records it should be possible to reconstruct a lengthy record of Quaternary sedimentary events. Unfortunately cave sedimentology is still in its infancy and Mendip cave sediments have only received serious attention in the past decade. Therefore, unlike the speleothem and faunal records, there is no large body of sedimentological work available from Mendip caves for analysis.

Cave Sedimentology

Cave sediments have only been studied seriously in Britain over the past 20 years and much of this work has been far from systematic. Most researchers have simply applied a suite of analytical techniques developed for surface sediment analysis to cave sediments, often without thought to the appropriateness of these techniques. In Germany and France cave sedimentology is much more advanced and complex. Weichselian stratigraphies have been constructed based upon the results of cave sediment analysis. However the interpretation of these sediment sequences in climatic terms has serious methodological flaws, particularly the simplistic correlations of 'cold' climatic conditions with coarse deposits and 'warm' climatic conditions with fine deposits.

Recently a major review of cave sedimentology has been undertaken by Colcutt (1985). Although this is an unpublished PhD thesis it is over 1300 pages long and is intended to be *"essentially a textbook"* of cave sedimentology. No discussion of British cave sediments should be considered complete without some reference to this massive work, which not only presents the results of a decade of research on UK cave sediments, but also describes in detail the results of practically every paper ever written on cave sediments in English, French and German. It is therefore unfortunate that this work is incomplete: it is virtually devoid of any laboratory analysis since, as Colcutt states, *"...the laboratory equipment I needed was not immediately available"*. Colcutt was therefore unable to *"propose a coherent alternative to the established methodologies"* that he had found wanting, (Colcutt 1979, 1985). Instead, his primary concern is with the observation of structure in cave sediments as a means *"for the recognition of processes"*. However it is arguable that Colcutt is in grave danger of 'throwing out the baby with the bath water'. While observation of structure is undoubtedly the most important mechanism for hypothesis generation it is rarely reliable for choosing between competing hypotheses. For this, laboratory and/or quantitative methods are generally essential. Therefore this section will fall into two parts:

1) laboratory techniques will be discussed that are suitable for cave sedimentological analysis;

2) a number of Mendip region cave sites will be discussed, not as site reports (which will be published separately), but in order to illustrate the utility of those techniques.

C H A P T E R VIII

LABORATORY TECHNIQUES FOR CAVE SEDIMENTOLOGY

Introduction

Colcutt (1979,1985) has identified that the major problem with the majority of cave sedimentological studies is the application of a battery of analytical techniques to all sediment samples collected, regardless of the nature of the sediments or the sedimentary structures present. The laboratory analyses are often undertaken without first identifying what problems these analyses are being used to solve. This type of 'positivist' approach is invariably doomed to failure, since, while a large number of facts will be generated, unless they are generated within an analytical framework that is designed to address specific problems, the facts will remain meaningless data (see Chapter 1). A good example of this problem is found in Webb (1980) who carried out over 200 particle sized determinations on sediments from Boria Fusca cave in Italy. These analyses provided an excellent basis for describing the sediments, but Webb (1980) concluded: *"Unfortunately particle size analyses reported here have failed to provide any distinctive indication of past climatic variation."*

A primary reason for this failure is the lack of a conceptual framework as to what effect climatic variation will have on the particle size of sediments in caves in metamorphic rocks. The work of Webb has been cited because of the honesty of her conclusion rather than to imply that her analyses are in any way inferior to those of other studies.

However, once a conceptual framework has been developed, laboratory analyses often provide the most powerful scientific tool for problem solving. Unfortunately many cave sedimentological studies use techniques that have been developed for surface sediment analysis. These techniques are not always appropriate and are sometimes outdated. This chapter will examine the most commonly used laboratory techniques in cave sedimentological studies and attempt to suggest improved procedures.

Sampling

The primary problem with any sedimentological study is in first obtaining representative samples. Fortunately an extensive literature exists on both the theoretical and practical aspects of field sampling (eg BS812, BS1377, Bragg 1974, Carson 1967, Hedbury 1976). Unfortunately while many researchers take extensive care when field sampling, this same caution is often absent during laboratory sample splitting. Virtually all laboratory analytical procedures require the original field samples to be divided up into sub samples and this is frequently undertaken using a riffle box or by scooping a sub sample directly out of the original sample bag. Allen & Khan (1970) have examined the relative efficiency of five commonly used sub sampling methods using binary mixtures of particles of different size and density ranges. Allen (1981) has also examined the operator independence of three of these sub sampling methods (Table 8.1). These results clearly show that the spinning riffler is superior to the other methods, being the least operator-dependent, and yielding more accurate and precise sub samples. Furthermore, Allen & Khan (1970) demonstrated that as the percentage of fines (<157um) increases, the accuracy of the spinning riffler sub samples can increase, but the accuracy of chute riffler (riffle box) sub samples decreases. Since many cave sediments (particularly in Mendip caves) contain a large proportion of silt and clays, the sub sampling errors using any technique other than a spinning riffler are likely to be unacceptable considering that many other analytical techniques have precisions greater than 5%.

TABLE 8.1 : PRECISION AND OPERATOR DEPENDENCE OF SELECT SEDIMENT SAMPLING METHODS (modified from Allen & Khan 1970 and Allen 1981)

Method	Coarse and Fine Sand			Sugar-Sand Mixture		
	Standard Deviation %	Variance (%²)	Estimated Maximum Sample Error %	Standard Deviation %	Variance (%²)	Estimated Maximum Sample Error %
Cone & Quartering	6,81	46,4		5,76	33,2	19,2
Scoop sampling	5,14	26,4	17,1	6,31	39,8	21,0
Tree sampling	2,09	4,37	7,0	2,11	4,45	7,0
Chute riffler	1,01	1,02	3,4	1,10	1,21	3,7
Spinning riffler	0,125	0,016	0,42	0,27	0,073	0,90

Operator	Spinning riffler	Chute splitter	Cone and quartering
1	0,54	0,34	1,48
2	0,60	1,34	1,80
3	0,40	1,34	0,61
4	0,68	0,72	1,00
5	0,69	1,28	0,93
6	0,85	1,18	1,09
Average	0,64	1,00	1,20

Experience of using a spinning riffler has shown that it can be used to split free-flowing sediments down to approximately a one gramme sub sample but is unsuitable for smaller amounts due to the quantity of sample lost to the atmosphere during operation. A number of analytical techniques (particularly chemical analysis) require 100mg or 10mg samples. The optimum method of sub sampling to this level is by using a suspension sampler (Burt *et al* 1973). Unfortunately no suspension samplers are commercially available at reasonable cost. But a competent workshop can build one for around £100 (1983 prices). An alternative method is to sample from a stirred suspension using a syringe. However the efficiency of this method is operator dependent and precisions are usually inferior to that of Burt *et al's* suspension sampler (see Appendix 4). When obtaining a small sub sample it is important to keep the number of splits to a minimum. Emmerling & Tanner (1974) have shown that the compound error introduced by repeated splitting can be large, and have recommended that samples should be split no more than twice if this is feasible.

Particle Size Analysis

Particle size analysis is undoubtedly the most widely used analytical method common to virtually all cave sedimentological studies. They are often undertaken to aid sediment description, the cross correlation of horizons in different sections, and to identify sedimentary environments. Unfortunately most researchers are unfamiliar with much of the diverse literature on the problems of sediment size determination. So these problems will be considered in some detail.

The most accurate way of measuring particle size is by microscopy (Lauer 1966). Unfortunately the number of particles that must be measured for statistically significant results is usually so large that direct measurement is impractical. However microscopy remains a useful method for determining the efficiency of other techniques (Friedman 1962).

The simplest and most widely used particle size analysis technique is sieving, which is demonstrably superior to other methods such as rapid sediment analysers - settling tubes (Coleman & Entsminger 1977); as long as a mechanical shaker such as a Ro-Tap is used in preference to a sonic sifter (Wolcott 1978). For accurate sieving the sediment particles must be free flowing. Common treatments include removal of organic matter with potassium dichromate and 30% hydrogen peroxide and then washing with distilled water to remove salts (Carver 1971).

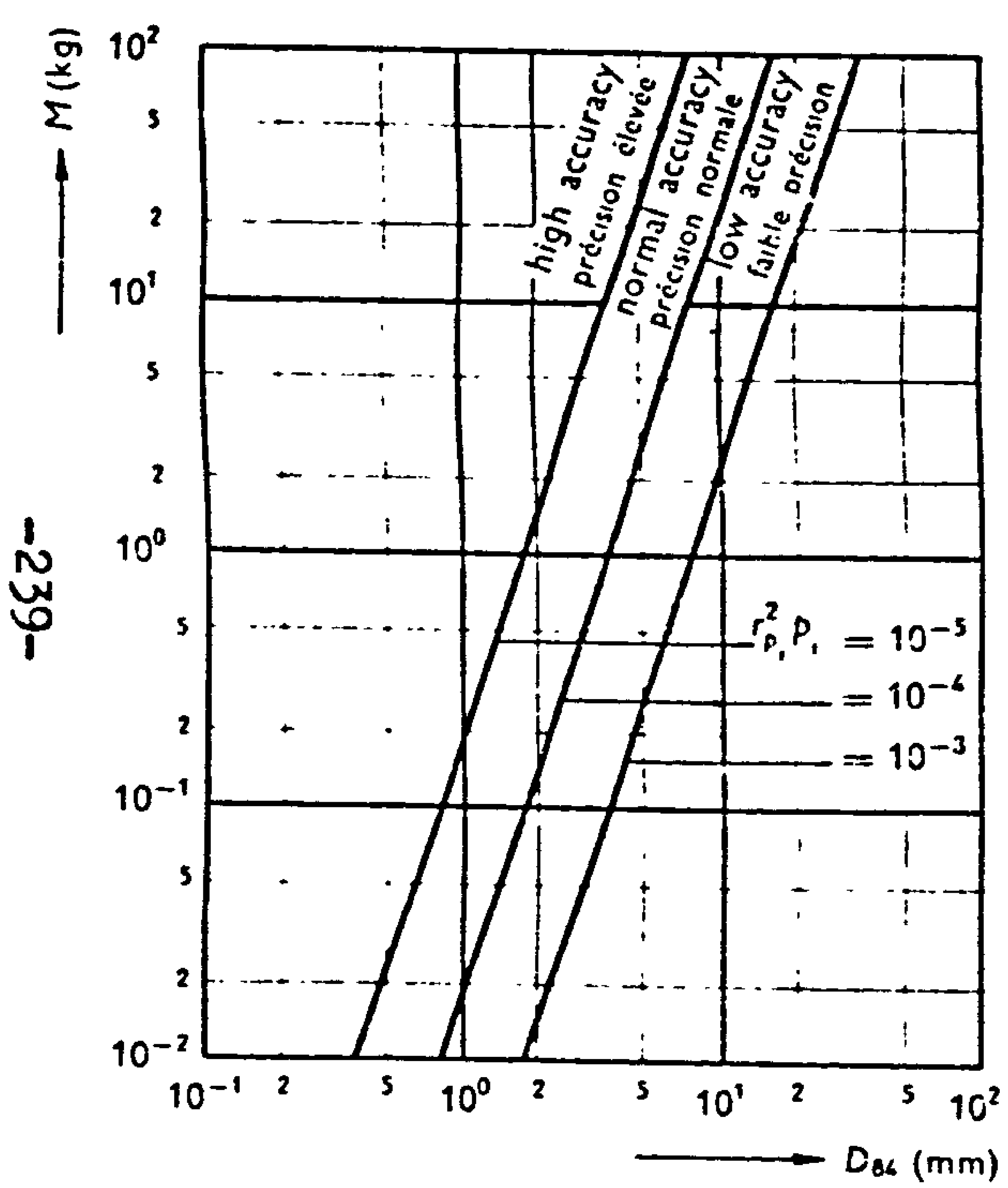
An attraction of sieve analysis is that only two variables need to be considered: the amount of sample and the length of sieving time. Early work by Shergold (1946) showed that overloading of sieves had a critical effect on accuracy which could be *"more effectively rectified by reducing sample size than by sieving for longer periods"*. He recommended that sufficiently small sample sizes should be used so that the weight of samples retained upon sieves of different sizes should not exceed a certain critical value. This idea has been adopted into the British Standard (BS1377). However the critical values sometimes differ significantly from those of Shergold (1946), although no explanation is given for these differences (Table 8.2).

Although sample sizes must be small enough not to overload the sieves they must be large enough to be representative. De Vries (1970) has calculated the minimum sample sizes required to obtain high accuracy (>1%), medium accuracy (>3%) and low accuracy (>10%) results (Figure 8.1a). For example, for a sample with a D84 of 5mm (84% is finer than 5mm), if high accuracy results are required 20kg of sample must be used. Therefore *"coarse sand and gravel do require samples too large to be sieved directly"* using standard 200mm sieves. To avoid sieve overloading large samples must be split, sieved independently,

TABLE 8.2 : TABLE OF SIEVE SIZES WITH MAXIMUM MASS TO BE RETAINED ON EACH.

BS Sieve Aperture width (mm)	(BS1377) 450mm dia. sieves (kg)	(BS1377) 300mm dia. sieves (kg)	BS Test sieve (mm)	(µm)	Max. Mass 200mm dia. sieves (kg)	(Shergold 1946) Max Mass 200mm dia sieves (kg)
50	10	4,5	3,25	-	0,300	
37,5	8	3,5	2,00	-	0,200	0,150
28	6	2,5	1,18	-	0,100	0,100
20	4	2,0	-	600	0,075	0,070
14	3	1,5	-	425	0,075	
10	2	1,0	-	300	0,050	0,050
6,3	1,5	0,75	-	212	0,050	
5	1,0	0,05	-	150	0,040	0,035
			-	63	0,025	0,020

FIG 8.1 A



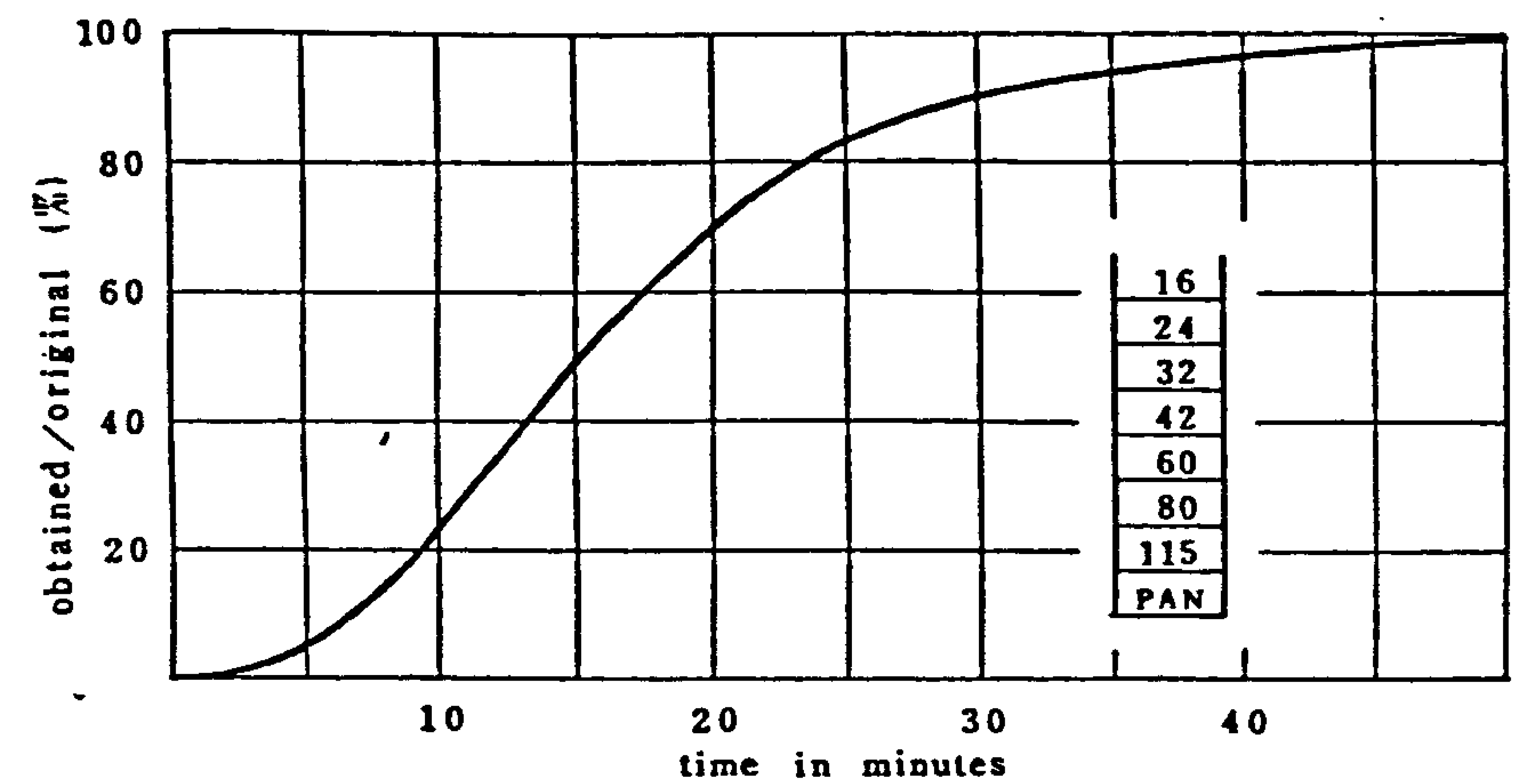


FIG 8.1B Accuracy of the sieving analysis by employing 16, 24, 32, 42, 60, 80 and 115 mesh sieves for all kinds of sediments.

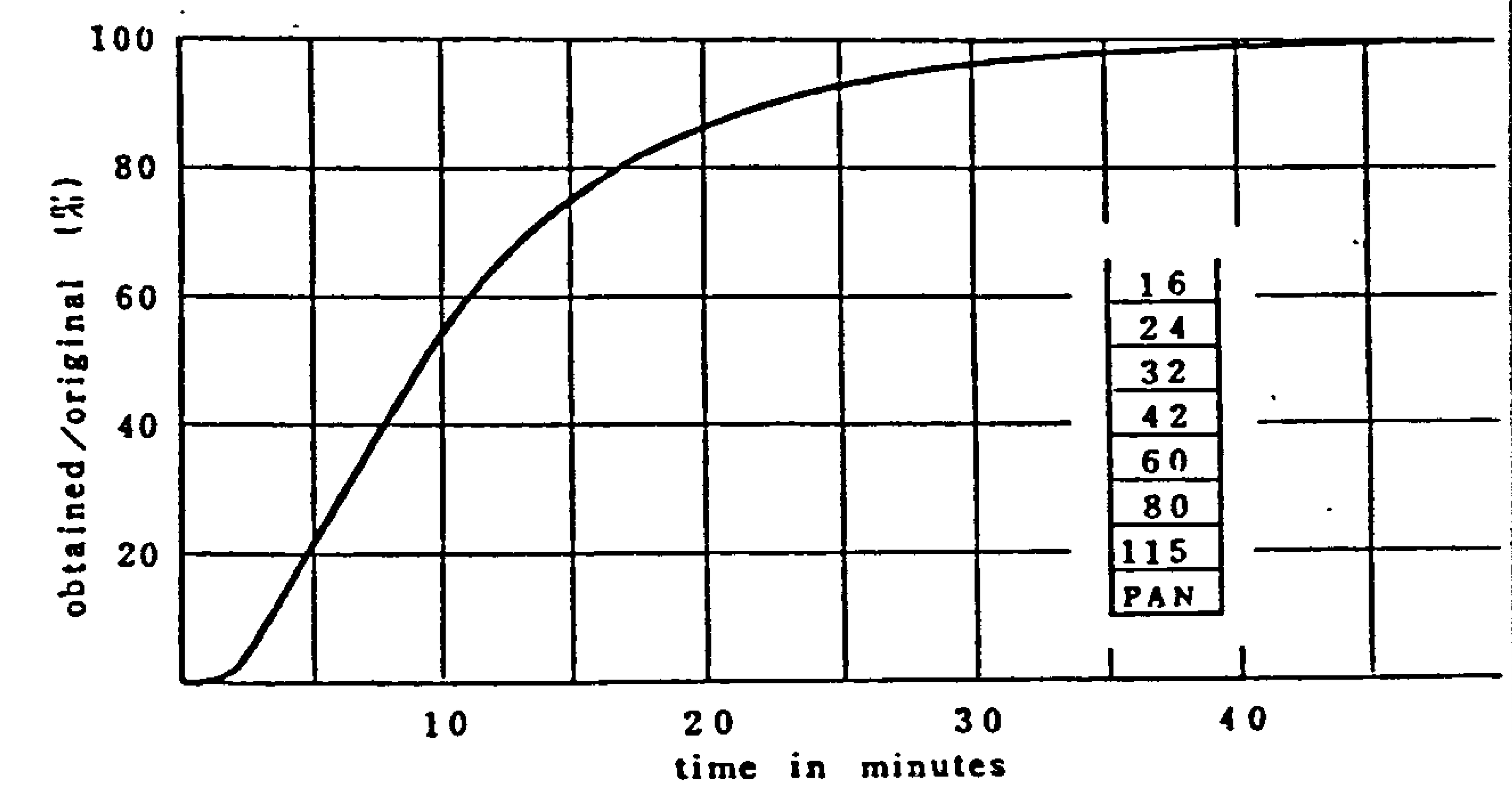


FIG 8.1C Accuracy of the sieving analysis by employing 16, 24, 32 42, 60, 80 and 115 mesh sieves for sediments finer than 115 mesh bu coarser than 170 mesh.

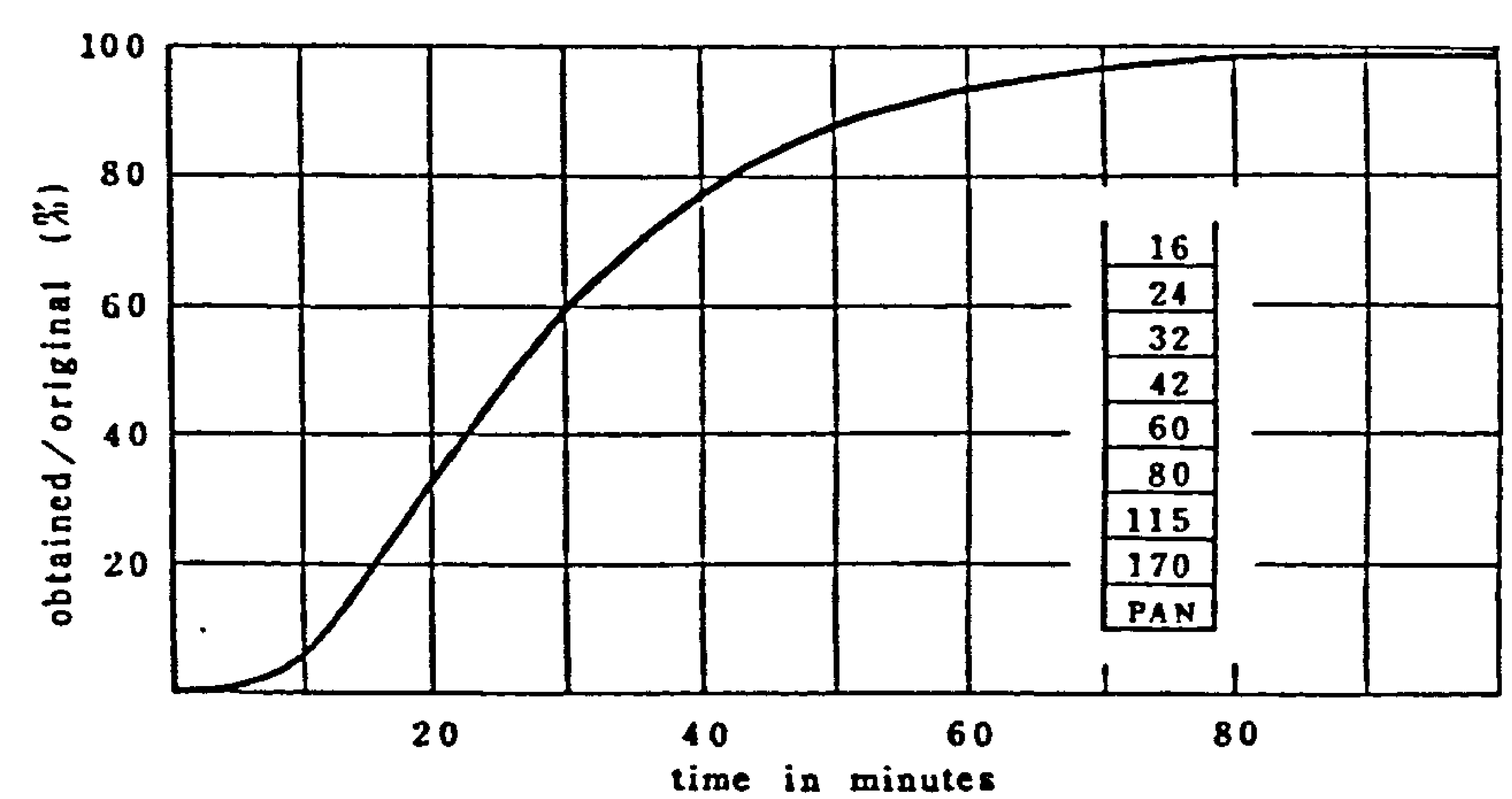


FIG 8.1D Accuracy of the sieving analysis by employing 16, 24, 32, 42, 60, 80, 115 and 170 mesh sieves for sediments finer than 170 mesh.

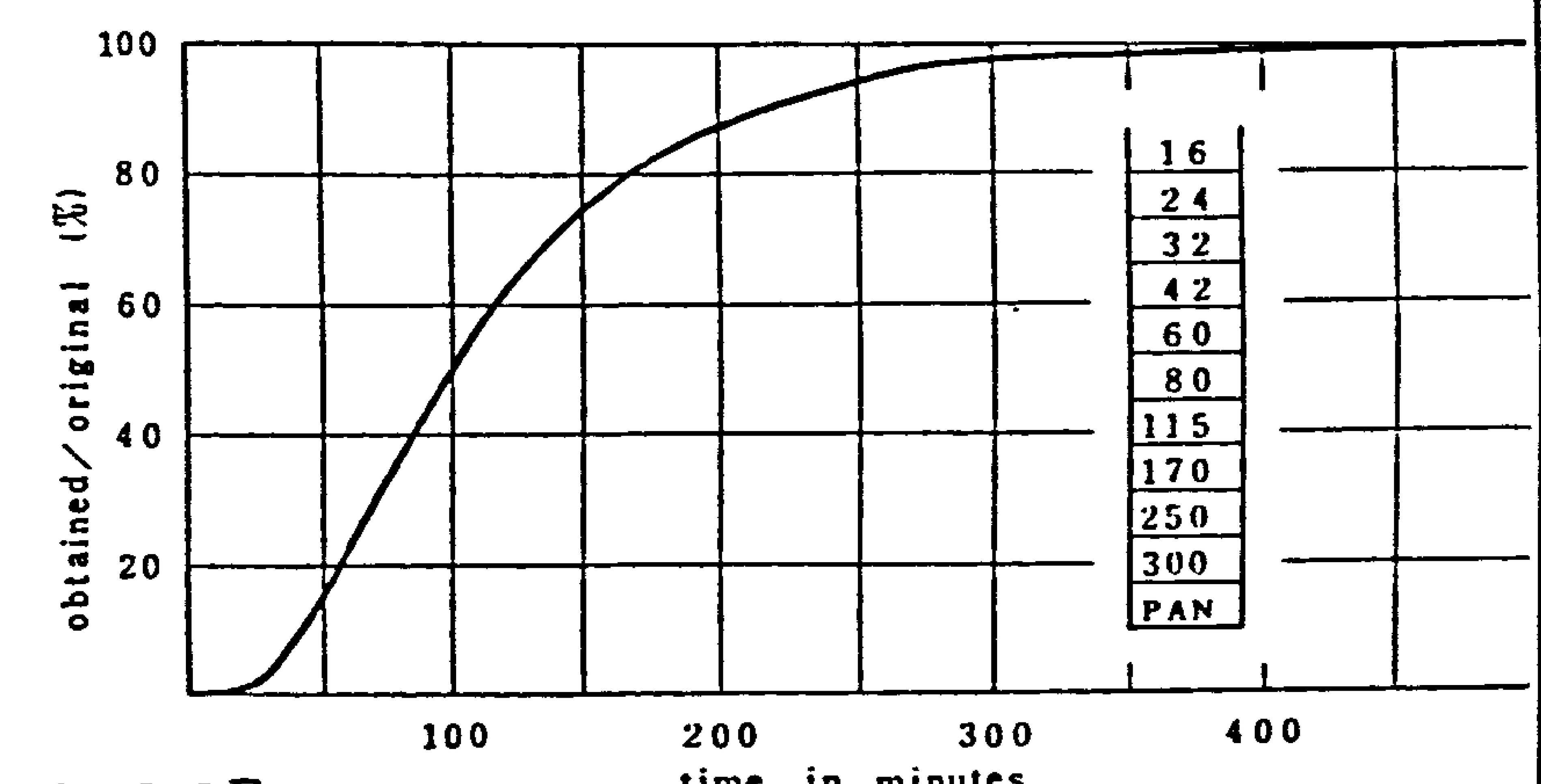


FIG 8.1E Accuracy of the sieving analysis by employing 16, 24, 32 42, 60, 80, 115, 170, 250 and 300 mesh sieves for sediments finer than 300 mesh.

(A) Minimum sample sizes required for high (1%), normal (3% accuracy particle size analysis (De Vries 1970).
(B-E) Accuracy Vs sieving time for particle size analysis with different sediment and sieve sizes (Mitzutami 1963).

the results summed (De Vries 1970). Accurate particle size analysis of cave gravels are usually impracticable because of the difficulty in transporting the large sample sizes required out of caves.

The length of sieving time required for accurate size determination using standard 200mm sieves and a Ro-Tap mechanical shaker has been considered by Mizutani (1963, Fig 8.1 b-e). For accuracies better than 5% a minimum sieving time of 30 minutes is required for sediments containing a significant proportion of particles finer than 0.125 µm. The length of sieving required for the accurate analysis of silts is impractical.

The commonest techniques used for particle size analysis of silts and clays are the pipette and hydrometer methods, of which pipette analysis is the most reliable (Sternberg & Creager 1961). Both methods are time-consuming, operator-dependent, and are based upon the assumption that all the sediment particles are spherical and will sink in accordance with Stoke's Law (Allen 1981). This assumption is seldom correct and although a number of correction factors have been proposed (Gibbs *et al* 1971, Gibbs 1972,) they have not been widely used. Even experienced operators can rarely obtain precisions greater than 5% (by weight) with soil samples (Bascomb 1968).

A large number of alternative methods have been developed commercially for use in industry; among these are sedimentation balances (Bostock 1952), rapid sediment analysers (Zeigler *et al* 1960), centrifugal pipette and photosedimentometer (Burt & Kaye 1966, Burt 1967) and Coulter counters (Lines 1973). However, problems are encountered with all of these methods, although they provide more rapid particle size results than conventional sedimentation methods. The analytical precision achieved is often inferior. Recently (*Circa* 1980) laser granulometers have been developed commercially that combine the advantages of rapid analysis with accurate and precise results (see Appendix 4).

It is clear from this discussion that the particle size results presented in many geographical studies are extremely unlikely to have accuracies and/or precision better than 5% and may well contain much larger errors. It is therefore surprising that these substantial errors are not immediately obvious from the presented results. A possible explanation for this is that size determinations are generally reported as cumulative percentage plots on semi-log scales, where within and between sample variation is represented by brakes of slope and by the vertical distance between sloping lines. Kolata (1984) has argued that these perceptual tasks are beyond the ability of most people "irrespective of their background" (Figure 8.2). Therefore although cumulative percentage plots may adequately record the data, they can be highly deceptive when judging the difference between two samples.

Particle Shape Analysis

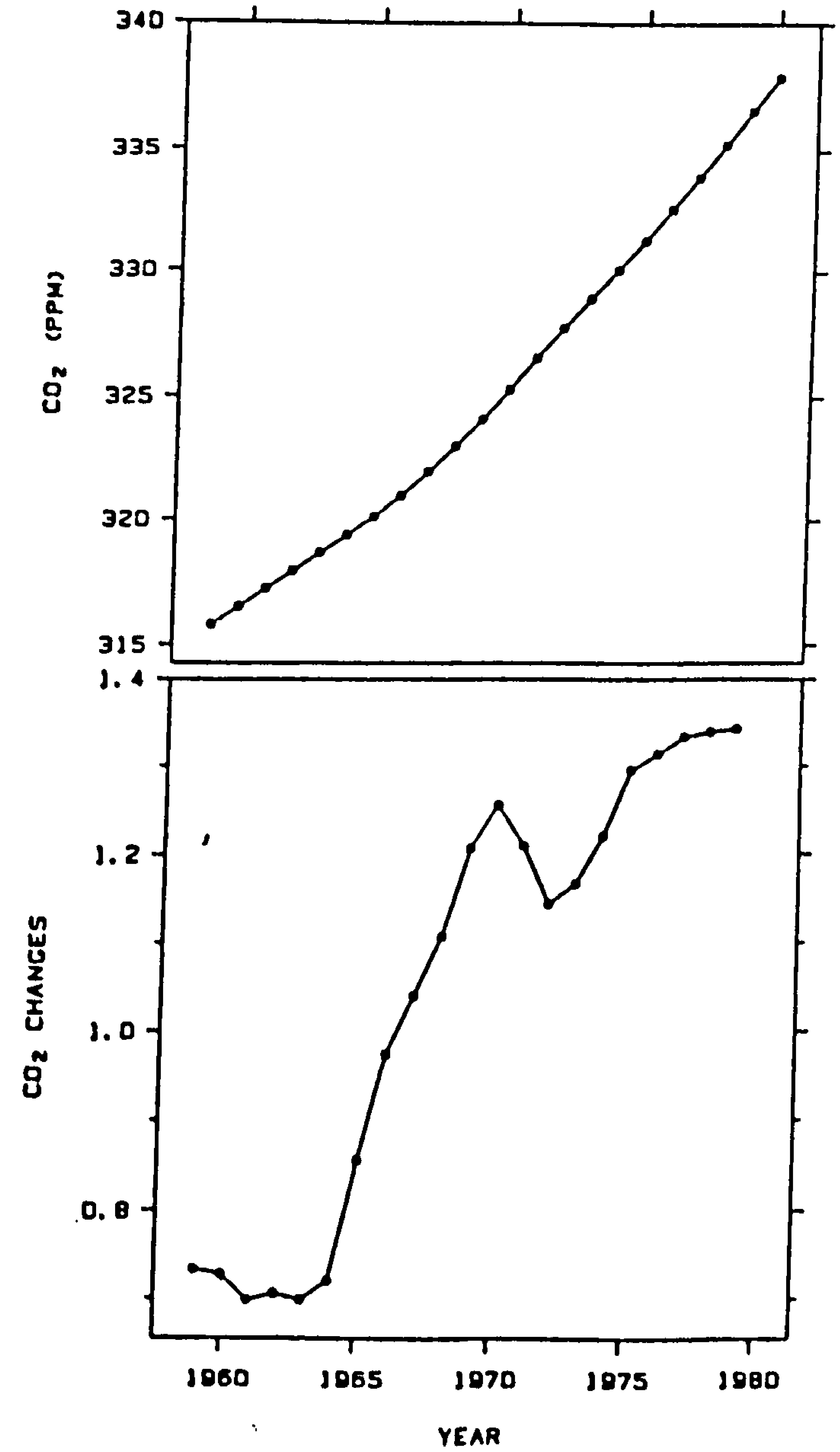
After particle size analysis, particle shape determination (particularly of clasts) are the most common analytical technique applied to cave sediments. This is not surprising considering that clasts of all sizes from gravel to boulders are extremely common in cave sediments, and they usually from the predominant autochthonous element in the cave deposits. Shape analysis is therefore frequently undertaken to try to establish palaeoenvironmental conditions within a cave.

Clast shape studies can be sub-divided into two main groups:

1) those on cave gravel which are primarily concerned with fluvial depositional environments, and

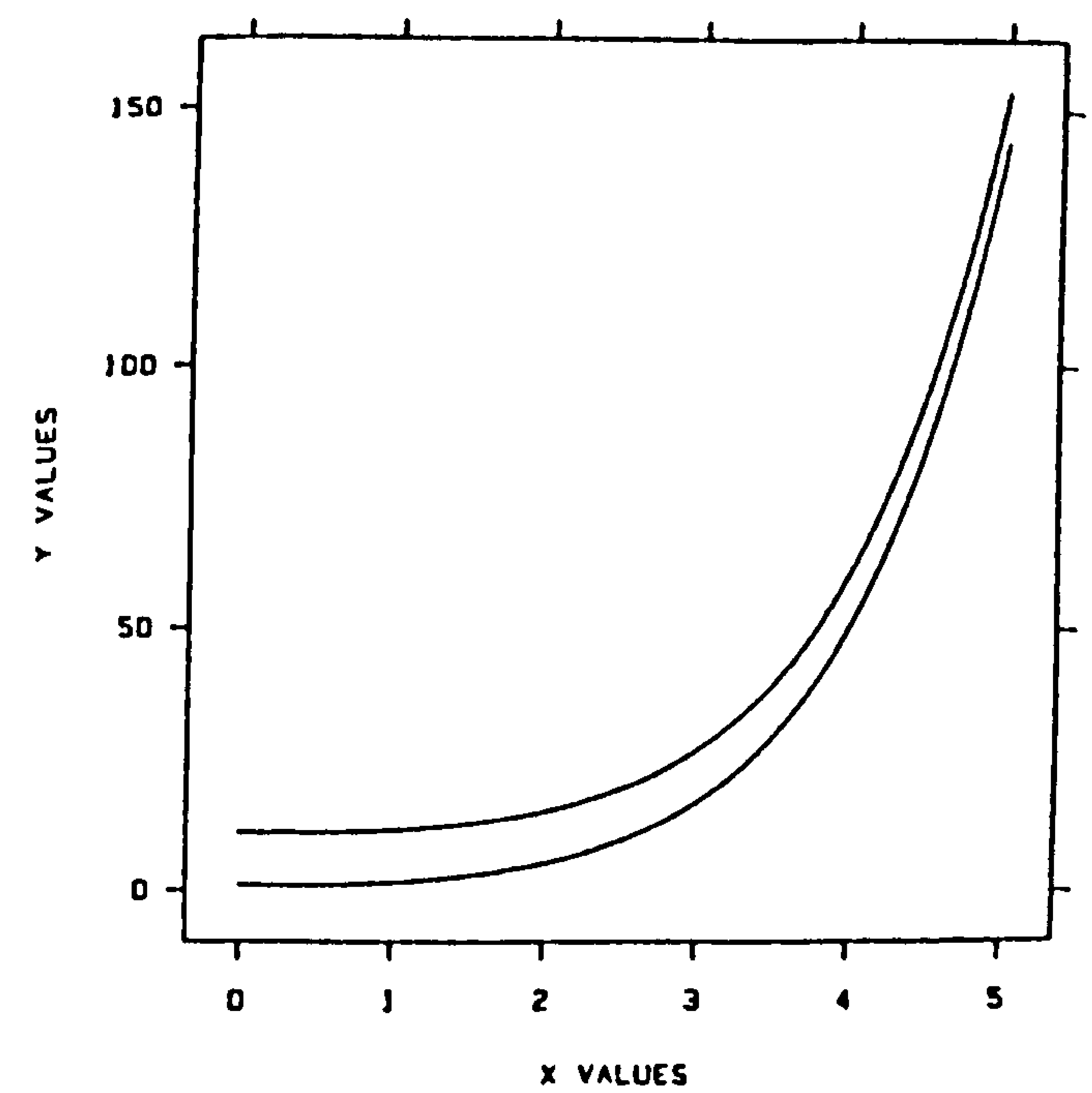
2) those on 'angular screes' designed to detect periods of periglacial conditions and/or subsequent weathering.

FIGURE 8.2 : Graphs to illustrate the problems of judging changes in slope and the distance between vertical lines (Kolta 1984).



Slope is hard to judge

The visual impression from the top panel is that the rate of change of atmospheric CO_2 is constant from 1967 to 1980. But in the bottom panel, where the yearly changes are graphed, it can be seen that there is a dip in the rate of change around 1970.



Vertical distances can be deceptive

The vertical distances between the curves are equal, although most people would guess that the curves become closer together in going from left to right.

This latter type of study is by far the most common, as with a few notable exceptions (eg Gospodaric 1974a,b, Bull 1978), cave gravel deposits have received virtually no attention, which is surprising considering the amount of hydrological work that is undertaken in Karst areas.

Particle form studies on 'angular scree' are frequently based upon the model of Laville (1976) who has argued that, all other things being equal, two extreme conditions can be considered:

"1) A cold period, characterised by an intense and prolonged annual cycle. The results will be a frost shattering of the roof of the rock shelter into large fragments; there will be concurrent sedimentation of these congelifracts, which will result in a protection more rapid and efficient with the intensity of freezing...

2) The case of minor ablation...the ablation is limited by moderate daily freezing. There will be fragmentation of small pieces and a crumbling of the rock surfaces..."

Laville (1976) goes on to argue that scree deposits resulting from intense freezing are characterised by 'frost shattered pebbles' whereas minor ablation deposits will contain fissured pebbles. Therefore Laville's model predicts that angular screes with large clasts result from intense cold periods whereas screes with smaller clasts will result from less severe climatic conditions. While this self-contained model may be correct, Colcutt (1985) has argued that the assumption it is based upon (eg that all other factors are equal) are highly unlikely to be valid. Colcutt (1985) also notes that limestone screes can actively be produced under interglacial conditions and concludes *"The present author remains very pessimistic about the chances of recovering anything more than general indications concerning cold climate."*

Nevertheless it remains a truism (that most cave scree studies are based upon) that scree formation is not only more rapid under periglacial conditions but that the scree also 'looks' different. This is the implicit assumption behind the identification of frost slabs (plaquettes) which are defined as any rock whose thickness is less than a quarter of its length (see Bonifay 1956,1962, Laville 1964,1971, Miskovsky 1971). This definition is unsatisfactory since a number of different shaped rocks (eg plates, wedges, trapezoids) can all fulfil this requirement. This example highlights the major problem of all cave sediment particle shape studies which have either measured shape using a 'one-dimensional' summary statistic and/or visually divided particles up into an arbitrary number of categories based upon their perceived 'roundness/angularity'.

One-dimensional indices fall into two groups: flatness/sphericity indices and roundness indices. Flatness/sphericity indices are all calculated from a combination of a particle's three major axes (a, b, and c measured orthogonally) (Krumbien 1941). Unsurprisingly a number of these indices are highly correlated for example Cailleux (1947) flatness index (a + b/2c) has been found by Orford (1975) to be inversely correlated with Sneed & Folk's (1958) sphericity index $((C^2/ab)0.333)$. Roundness indices tend to simplify the definition of roundness *"by restricting curvature measurements to the radius of the sharpest corner (r), and using the a and b axis respectively* as a *notional inscribing radius"* (Orford 1981). Commonly used indices are those of Cailleux (1945) (2r/a) and Kuenen (1955) (2r/b). However, Barrett (1980) has noted that all measures based upon *three-dimensional axis are not satisfactory discriminators of some forms. In particular they do not separate particles with triangular, rectangular and pentagonal cross sections."* Roundness indices generally have little discriminating ability with limestone clasts since many limestones (particularly in the Mendip region) tend to retain some texture even after fluvial transportation and gravel deposition (see Boreland 1985, Macklin 1985).

Subjective visual classifications are also problematic since they are highly operator-dependent and even the same operator can have difficulty re classifying the same sample exactly (Allen 1981).

There is also no general agreement on the number of categories into which samples should be sub-divided; for example Farrand (1975) working on clasts from French caves chose four categories, whereas Madeyska-Niklewska(1971) working in Polish caves used seven categories. There is also no agreement in studies on clasts from non-cave-environments. For example Olsen (1983) uses four categories whereas Lees (1964) and Powers (1953) both used more than ten categories.

It is clear from this discussion that although there may be differences in shape between cave limestone scree deposits formed in periglacial environments compared to temperate screes, the quantification methods used in all previous cave particle form studies are unable to adequately measure these differences. Higher resolution studies will be necessary if further progress is to be made. Although it is possible to record clast shapes in three dimensions using techniques such as holography, the amount of data generated by such methods is vast, which makes further analysis difficult. However a number of two-dimensional quantification techniques have been developed since the 1970s of which the radial fourier technique is the most widely used (Clark 1981). This method was first developed by Ehrlich & Weinberg (1970) who established that the digitised outline of a clast laid on its most stable axis could generally be adequately characterised by the first twenty harmonics of a standard fourier series (Figure 8.3; see Appendix 5). Two-dimensional shape analysis may allow differences in the shape of cave sediment particles to be distinguished if a conceptual theory in shape can first be established.

The Shape of Clasts in Limestone Rockfalls

All limestone clasts in Mendip cave sediments are derived from material that has fallen from free rock faces. No such clasts are initially spherical or ovate (in the Mendips), all have angular forms which may subsequently become rounded by weathering and/or erosion. Gagen *(per com)* has argued that all limestone clasts found from rock

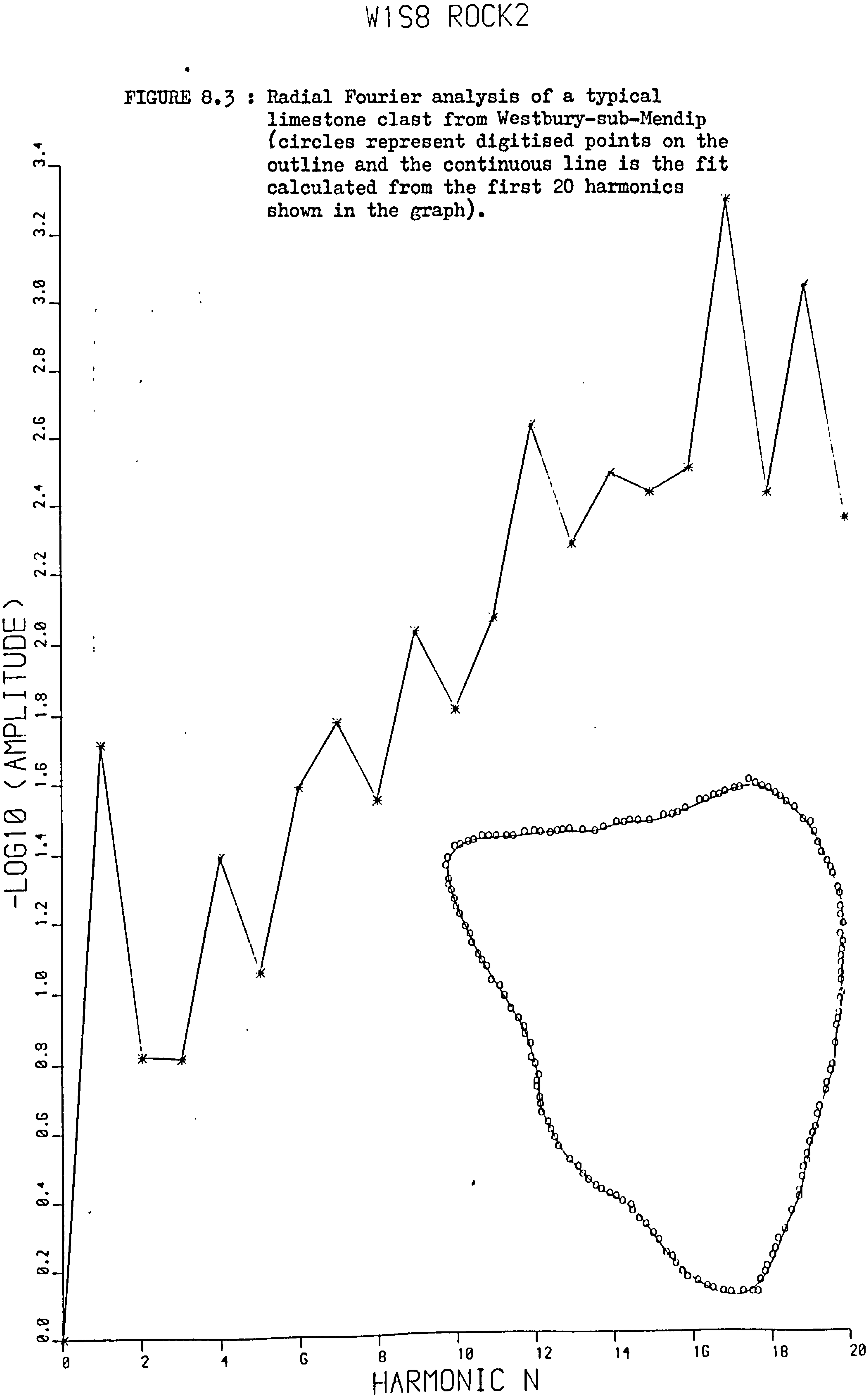
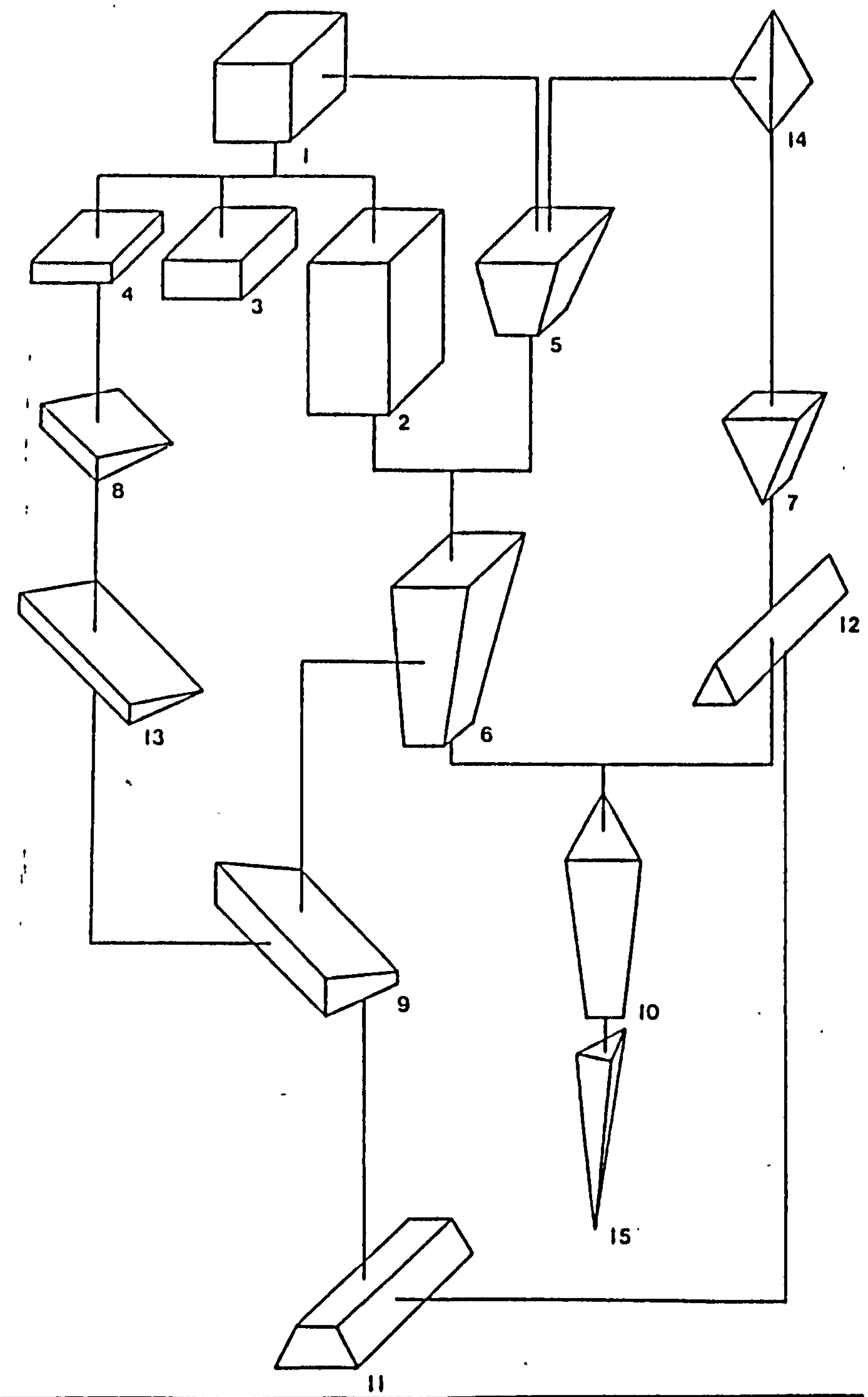


FIGURE 8.3 : Radial Fourier analysis of a typical limestone clast from Westbury-sub-Mendip (circles represent digitised points on the outline and the continuous line is the fit calculated from the first 20 harmonics shown in the graph).

falls in Derbyshire quarries can be characterised by just fifteen basic shapes (Figure 8.4). Irregular shapes have been excluded but these are relatively rare (Gagen per com). The study of approximately five hundred limestone clasts from sediments of various ages in eleven Mendip caves has indicated that all relatively unweathered clasts can be categorised by these fifteen shapes, and that all fifteen shapes are present (although some are very rare). Gagen (in prep.) has demonstrated that the relative proportions of clasts of different shapes is strongly influenced by climatic conditions (eg wedges tend to fall in the winter months and blocks tend to fall during summer). Therefore the possibility of inferring palaeoclimatic conditions from cave scree deposits exist if clast shapes can be quantified and clast then assigned to a shape category without operator bias.

It is clear that all fifteen shape categories will not have unique two-dimensional outlines; however they can all be expected to conform to six unique two-dimensional categories (Figure 8.5). To test this idea, perfect and textured outlines of these shapes were digitized (Figure 8.5) along with the outlines of a limestone clast belonging to each of the fifteen three-dimensional shape categories (Figure 8.6). These outlines were quantified using radical fourier analysis (Appendix 5) and then cluster analysis was performed on this data using the average linkage and Ward's algorithms on appropriate similarity matrices (see Appendix 3). The dendrograms of the cluster solutions are shown in Figures 8.7 , 8.8 and 8.9 and discussion of these results will be published elsewhere (Gordon & Gagen, in prep.). However it is clear from the Ward's method solution (Figure 8.8a) that elongated shapes (predominantly wedges) can be readily distinguished from blockey shapes (predominantly blocks and plates).

FIGURE 8.4 : The fifteen basic shape categories used to represent limestone rockfall clast shapes. (Drawn by P. Gagen.)



KEY

1 Block
2 Columnar Block
3 Planar Block
4 Plate
5 Block Wedge
6 Columnar Block Wedge
7 Planar Wedge
8 Plate Wedge
9 Rectilinear Block Wedge
10 Columnar Wedge
11 Planar Block Wedge
12 Rectilinear Wedge
13 Rectilinear Plate Wedge
14 Wedge
15 Splinter Wedge

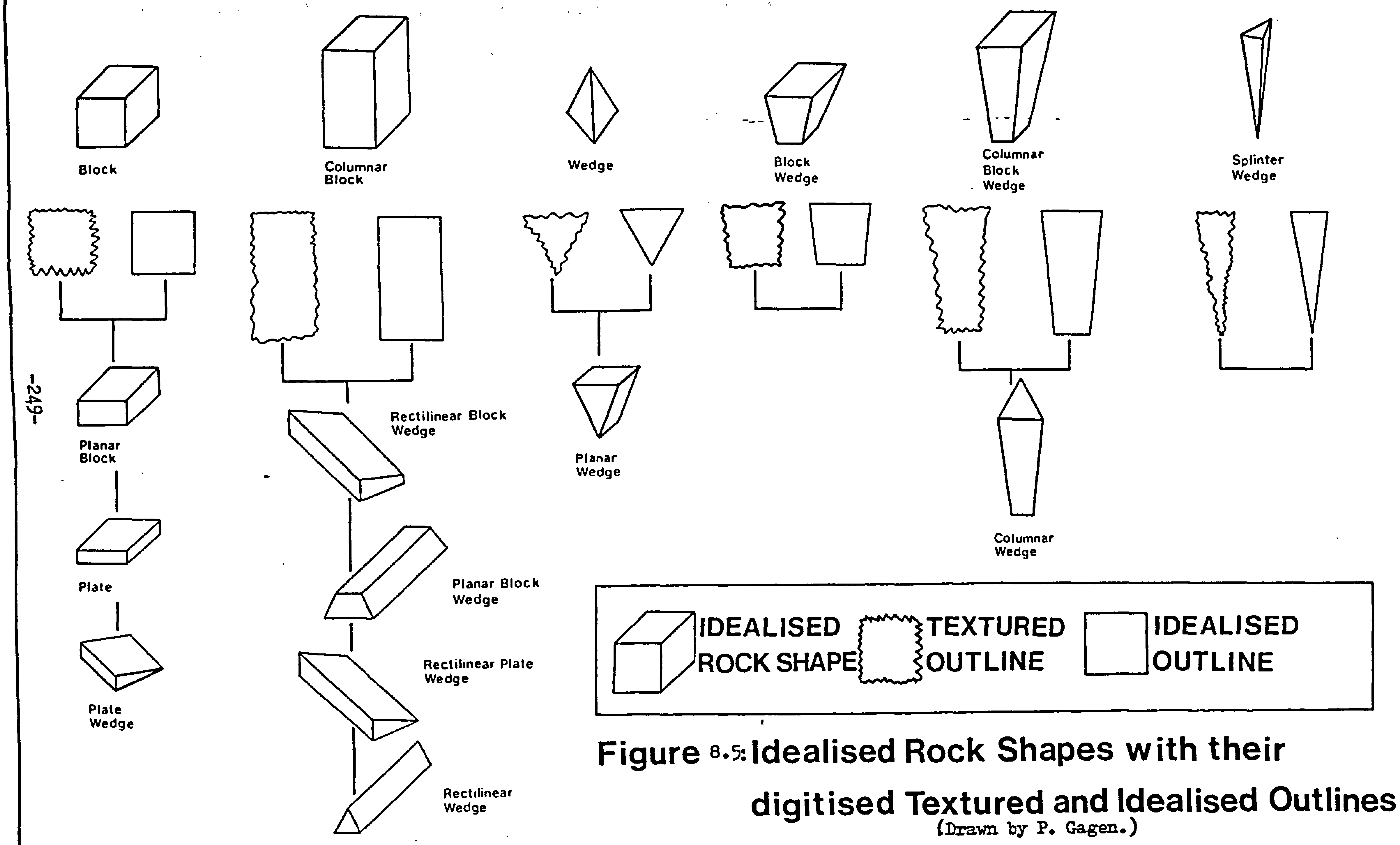


Figure 8.5: Idealised Rock Shapes with their digitised Textured and Idealised Outlines
(Drawn by P. Gagen.)

Figure 8.6: Digitised Outlines of Limestone Rocks (Drawn by P. Gagen.)

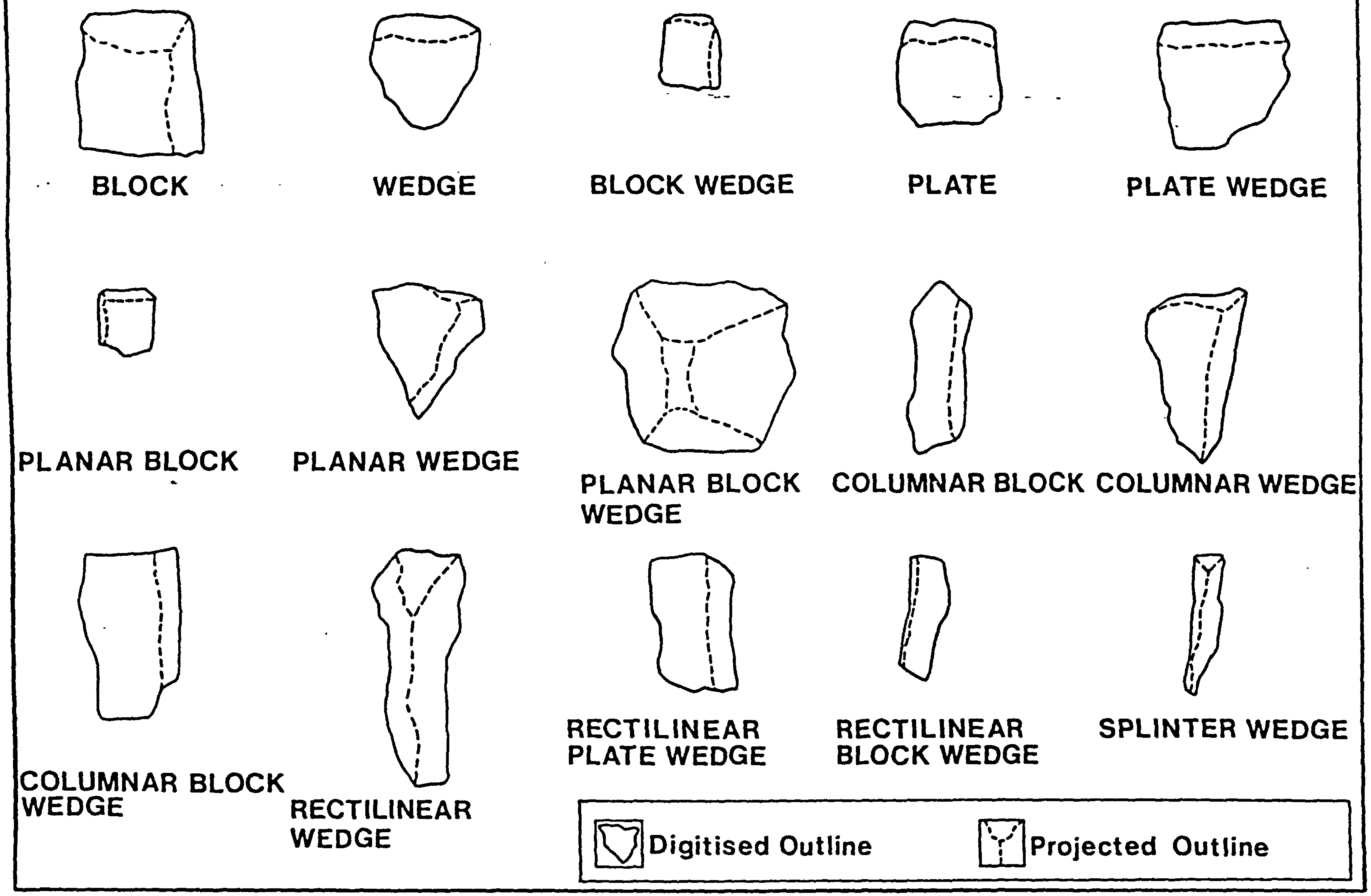


FIGURE 8.7A : TEXTURED AND IDEALISED ROCK SHAPES
—WARD'S METHOD USING EUCLIDEAN DISTANCE

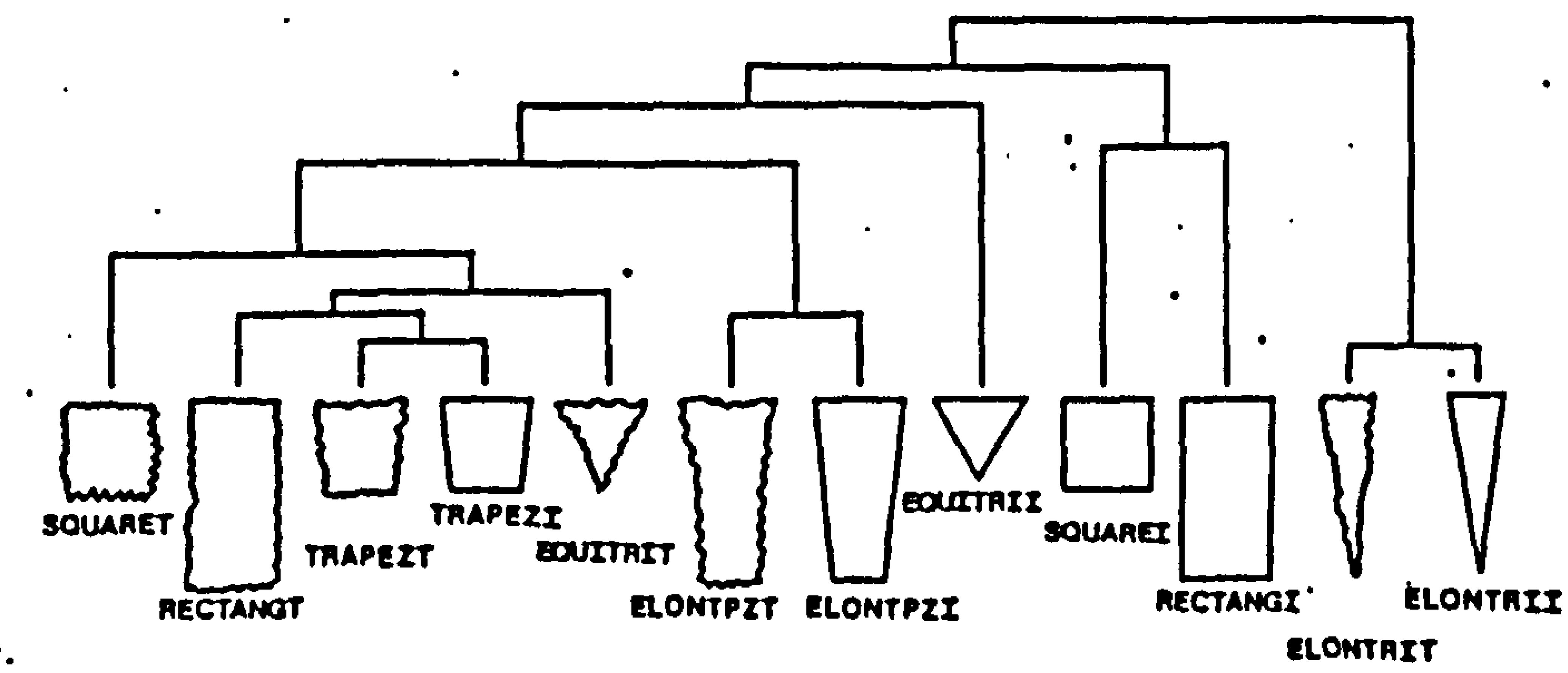
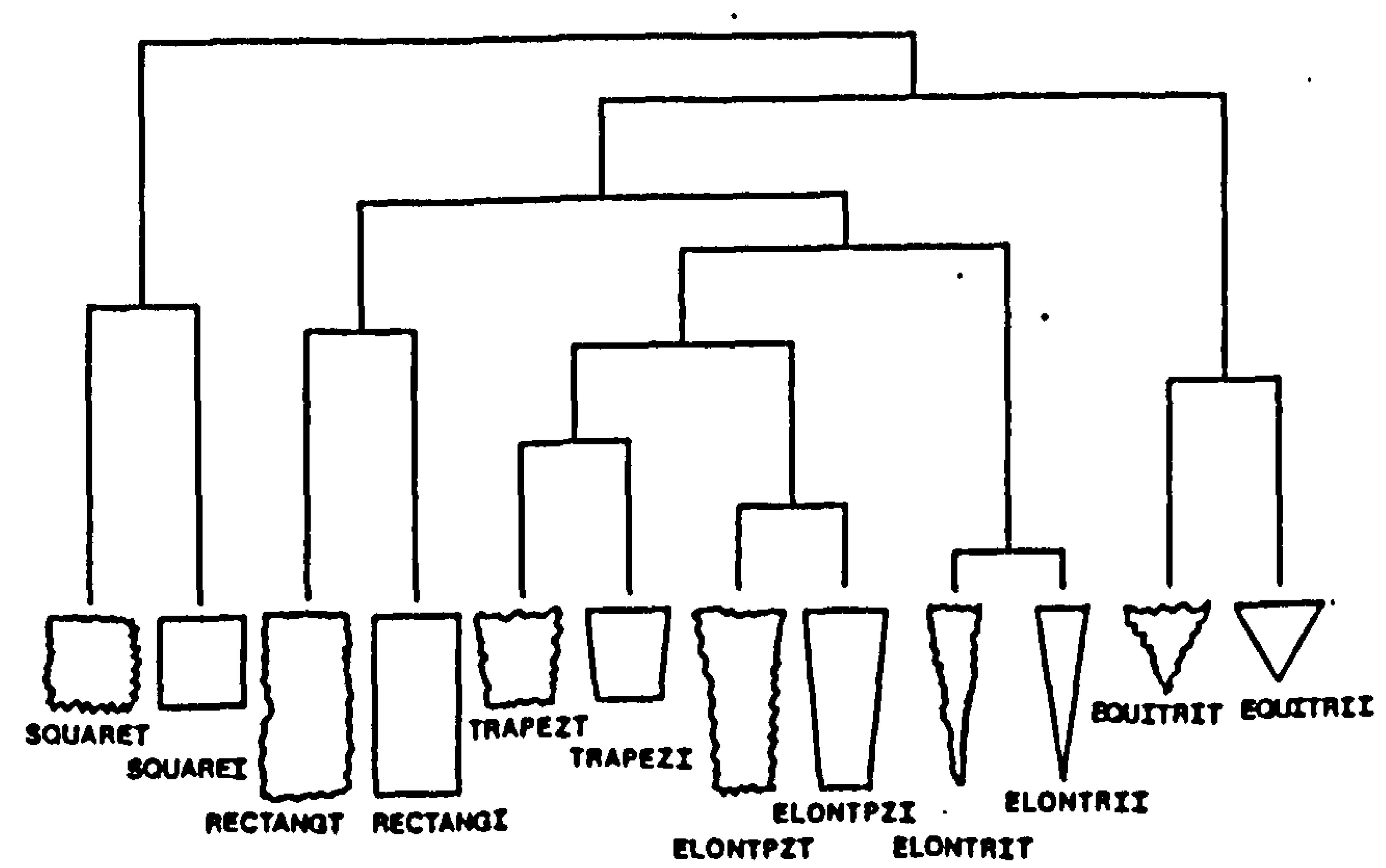
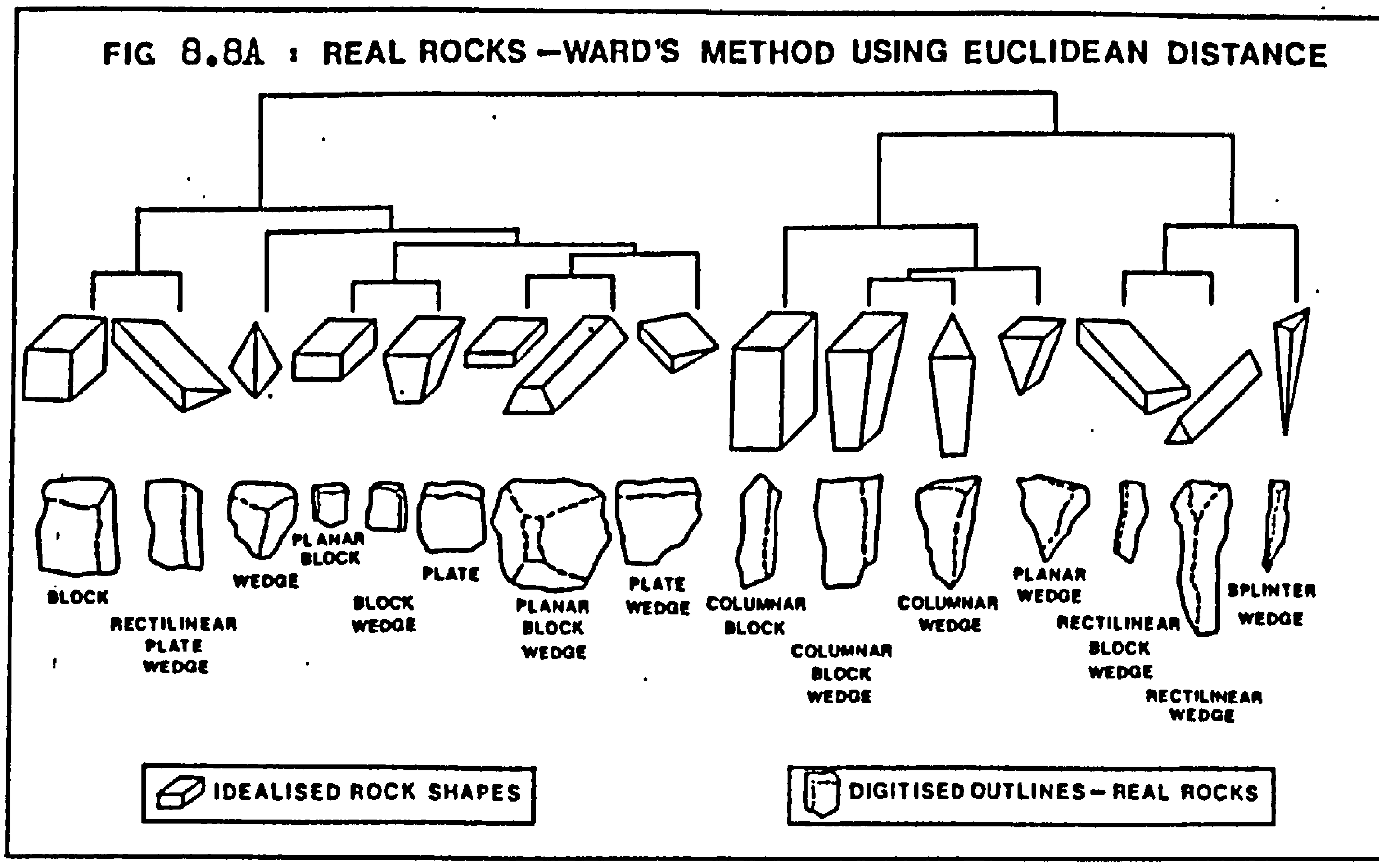
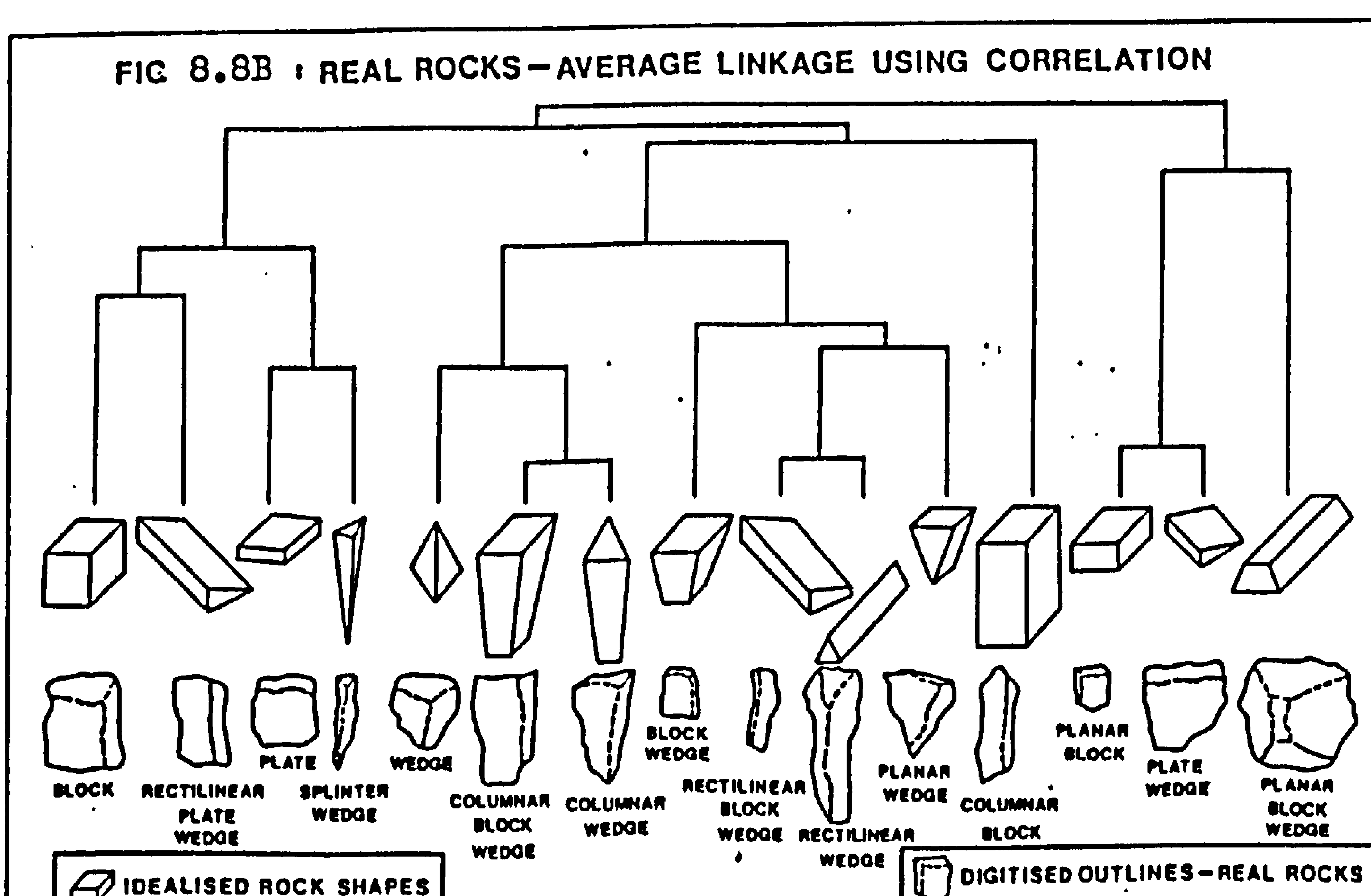


FIGURE 8.7B : TEXTURED AND IDEALISED ROCK SHAPES
—AVERAGE LINKAGE USING CORRELATION



(Drawn by P. Gagen.)





(Drawn by P. Gagen.)

FIG 8.9A: TEXTURED, IDEALISED AND REAL ROCKS
—AVERAGE LINKAGE USING CORRELATION

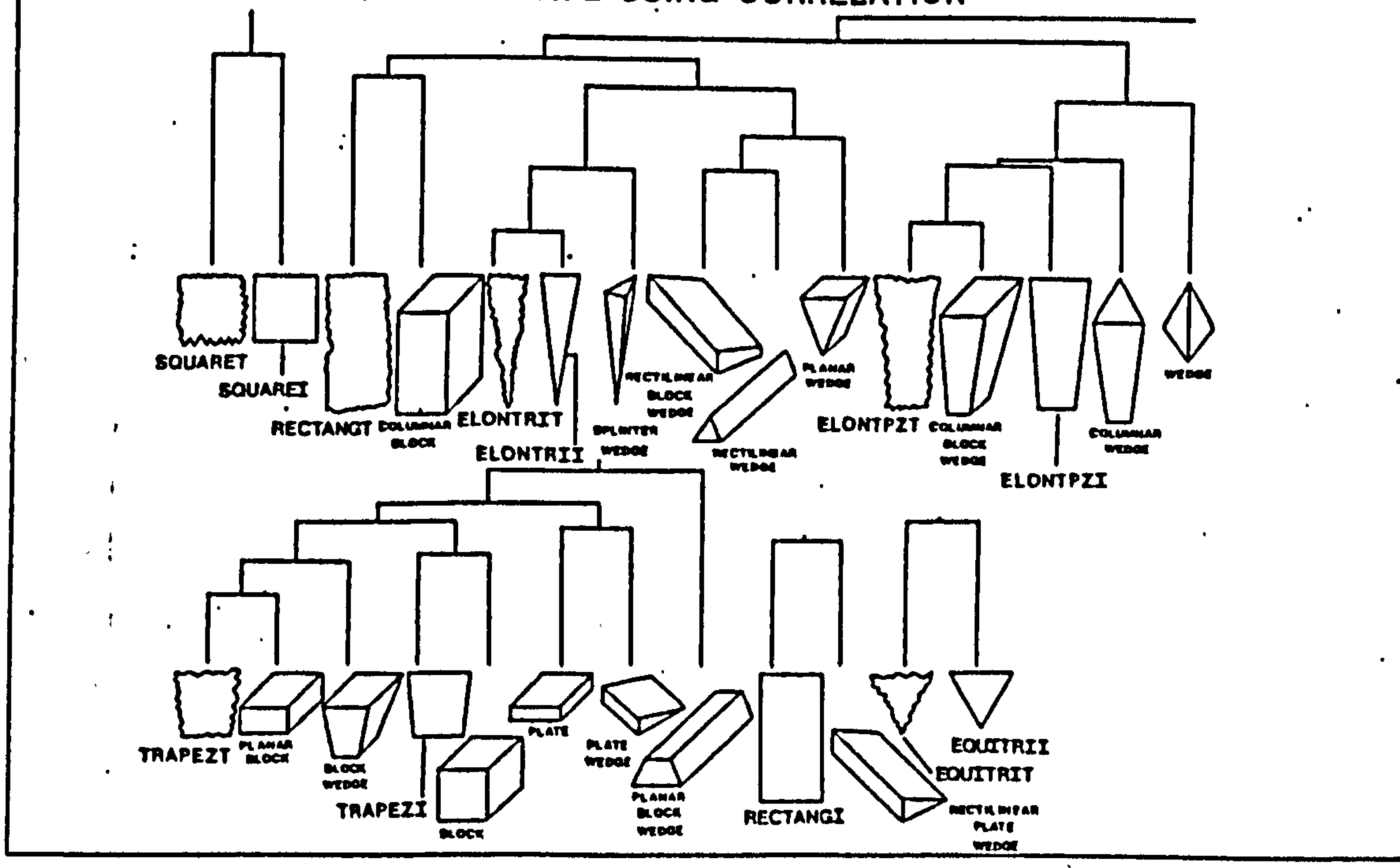
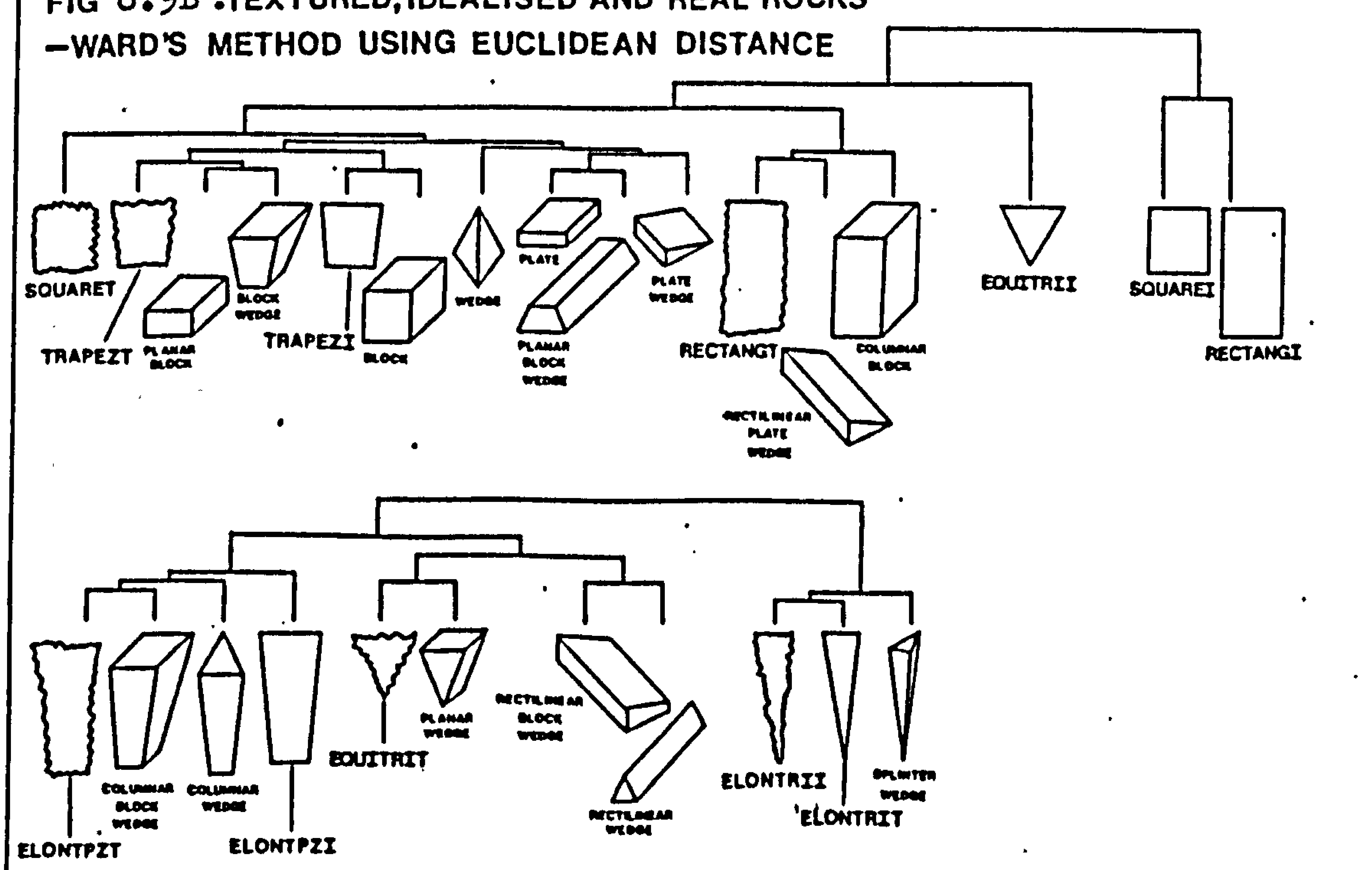


FIG 8.9B: TEXTURED, IDEALISED AND REAL ROCKS
—WARD'S METHOD USING EUCLIDEAN DISTANCE



(Drawn by P. Gagen.)

Physical Properties of Cave Sediments

To the author's knowledge no study of the physical property of cave sediment has ever been undertaken in the U.K. This is unfortunate since Colcutt (1985) has persuasively argued that the predominant mode of sedimentation in many non-swallet caves has been by 'debris flows'. Although it seems likely that some form of mass movement is responsible for most sedimentation in non-swallet caves, Colcutt's (1985) argument is based solely on structural and morphological evidence. He presents no quantitative or laboratory evidence that the sediments that he had examined are capable of mass flow. This situation is obviously unsatisfactory since different processes can produce similar forms and it is often difficult to accurately assess structure and form in restricted sections by the light of a caving lamp. Laboratory analysis of the physical properties of sediments can be particularly illuminating in assessing the nature and/or the likelihood of mass movement, and a vast literature exists on this subject. A full discussion of the range of physical tests that would be applicable to cave sediments is beyond the scope of this work. However, the measurement of a number of parameters that can be easily determined and are useful in assessing the possibility of mass movement, will be discussed.

Shakesby (1975) measured the plasticity index (PI) of Coombe rock deposits in south east England in order to establish if they were likely to have been emplaced by solifluction. However his use of the rolling bead test and the Casagrande apparatus (BS1377, 1975) to measure liquid and plastic limits is now outdated (Whyte 1982). The original definitions of liquid limit (LL) as the water content below which the soil would cease to flow as a liquid, and plastic limits (PL) as the water content below which the soil could not be rolled into a 3mm bead, have been reassessed. The liquid limit has now been redefined as the water content where sediment strength is $1.6KN/M^2$ (Whyte 1982, Wood 1982). This strength can be measured reliably and rapidly using a drop cone penetrometer, and British

Standards (BS1377) now recommend that the liquid limit is measured as the water content at which a 80±0.05g cone of 30±1° angle will penetrate 20mm in 5±0.5 seconds when placed on the soil surface. This test has been shown to be theoretically valid (Houlsby 1982) and applicable to a wide range of sediments (Campbell *et al* 1980, Mullins & Fraser 1980).

The plastic limit can also be measured reliably using a drop cone penetrometer if Skempton & Northey's (1952) data showing that the plastic limit is equal to 100 times the liquid limit, are accepted (Wood 1982). Belviso *et al (1985)* have shown that if cone penetration is plotted against water content the slope of the line will be equal to the plasticity index. Therefore the plastic limit can be calculated since PL = LL + PI.

Figure 8.10 shows the drop cone penetrometer results on a typical calcareous sediment sample from the mid Pleistocene levels at Westbury-sub-Mendip. The liquid limit is 35.8% and the plasticity index is 3.5, which is a low value compared with most sediments and indicates that this deposit could easily have undergone mass movement (plasticity index values are generally less than 10 from the calcareous sediments at Westbury-sub-Mendip).

Chemical Analysis of Cave Sediments

Most standard chemical analytical techniques developed for surface sediment analysis are directly applicable to cave sediments (eg Hesse 1971). However problems can arise with organic carbon determinations. Several investigators have used the loss-on-ignition method of Ball (1964) despite the fact that this method is designed for non-carbonate sediments. Figure 8.11 (Briggs *et al* 1984) illustrates the problems that can occur; the % $CaCO_3$ is highly inversely correlated with both organic phosphorus and organic carbon. The Pearson's Product Moment Correlation Coefficient are respectively -0.729 and -0.894, which are both significant at better than 1%

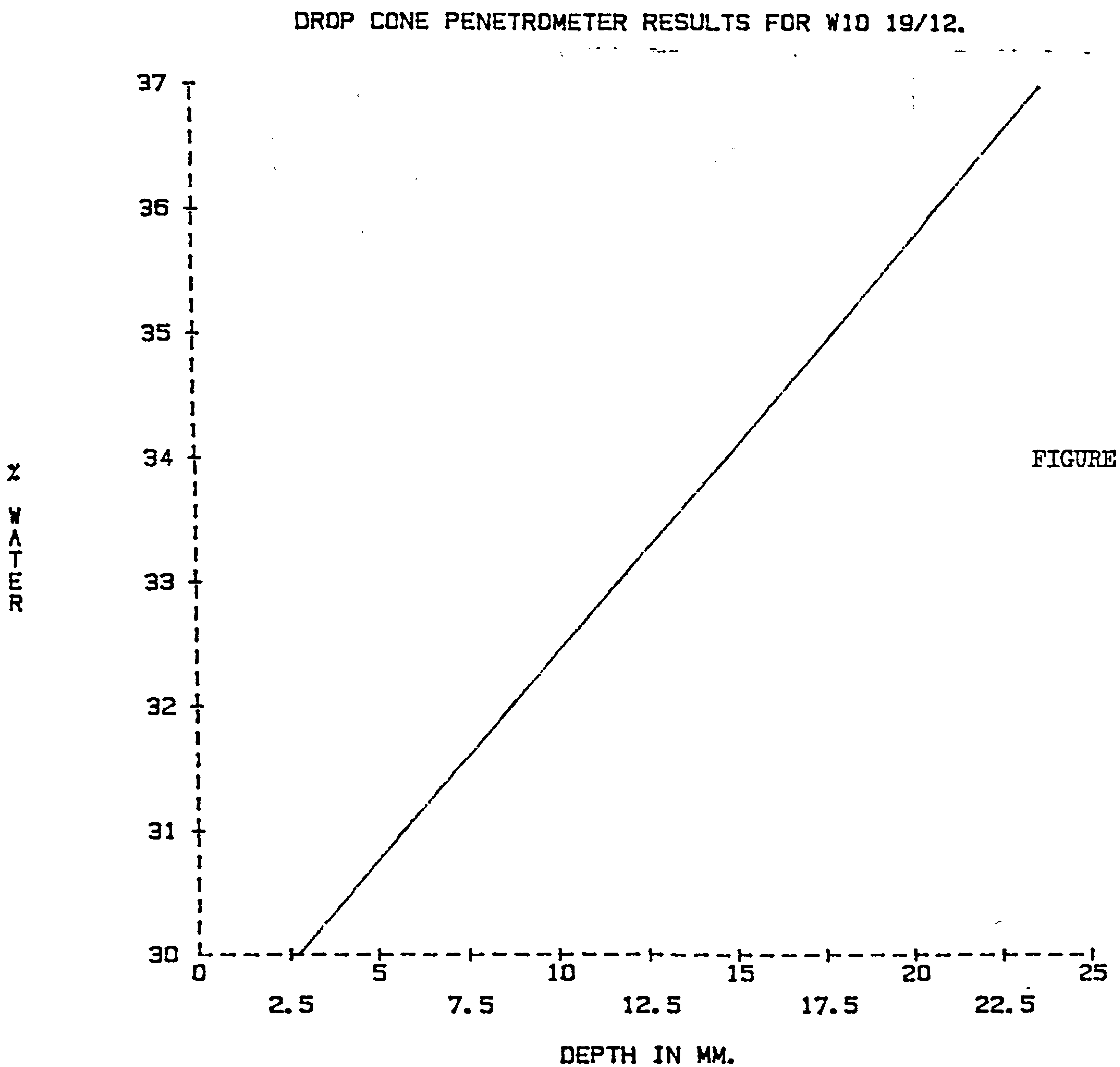


FIGURE 8.10 : Drop cone penetrometer results from a typical mass movement deposit at Westbury-sub-Mendip.

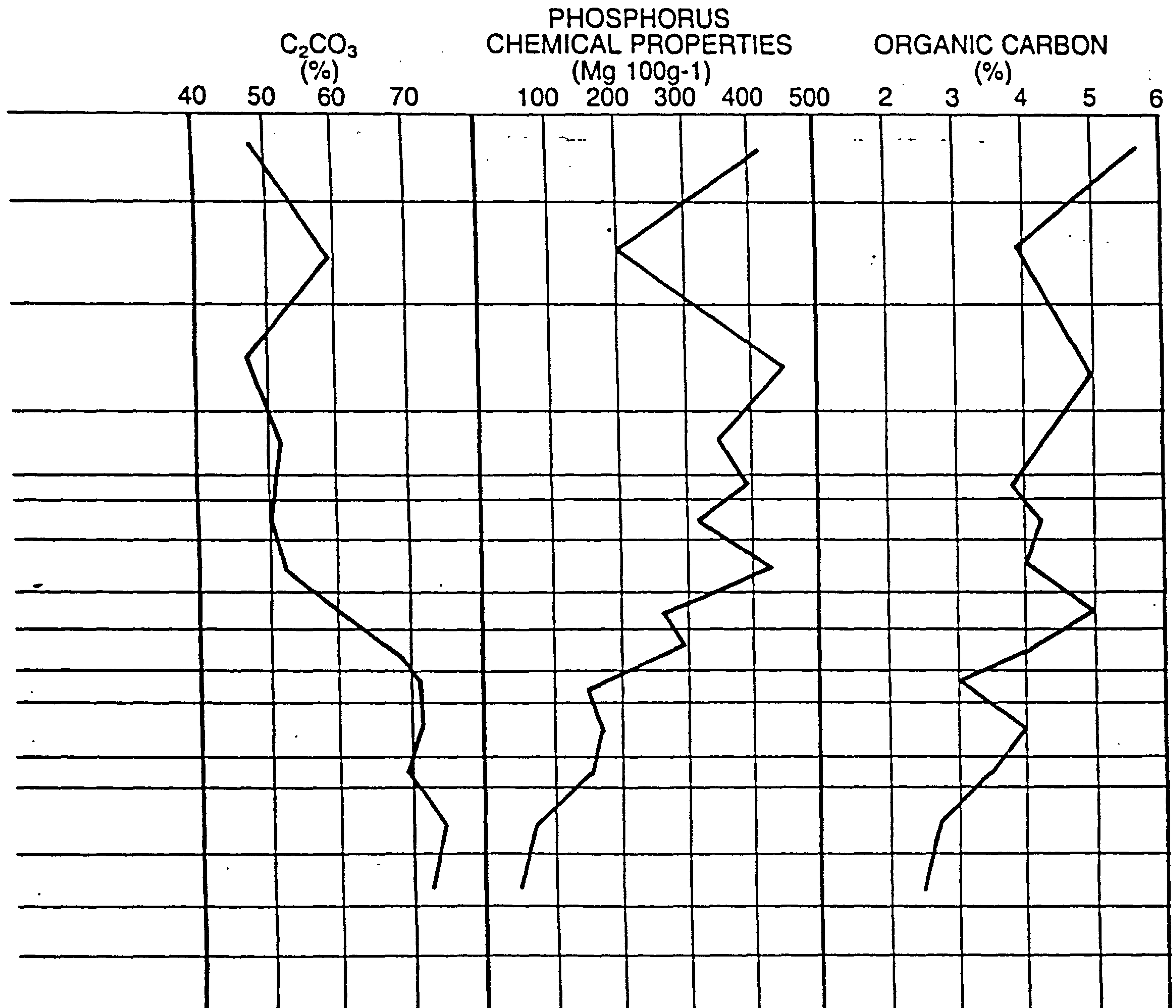


FIGURE 8.11 : Chemical analysis results from Dog Hole fissure sediments, Creswell Crags (Briggs et al 1984).

(Spearman rank correlation and regression analysis give similar results). It seems unlikely that these results are correct as other researchers who have determined organic carbon concentration by titration methods have not reported such high correlations.

A number of wet oxidation titration methods have been used to determine the organic carbon content of soils, of which the method of Shaw (1959) is probably the most accurate (Bremner & Jenkinson 1960). However precision can be problematic with all titration methods, possibly due to the small sample sizes required (less than 0.5g). Recently modified elemental analysers have been developed which can rapidly determine both organic and inorganic carbon content on the same sample (Moriarty & Barclay 1980, Krom & Berner 1983). However these machines are expensive and not widely available.

An alternative method is to use the accurate loss-on-ignition technique of Ball (1964) after first removing inorganic carbon using an acid anti-oxidant solution such as that of Allison (1960) (eg 57ml of concentrated H_2SO_4 and 92g of $FeSO_4 7H_2O$, dissolve to make a 1000ml solution of approximately 2N acid with 5% $FeSO_4$). Once the inorganic carbon has been dissolved the residue should be washed twice with distilled water before drying and combustion. Table 8.3 shows the precision of this method with typical Mendip cave sediments.

TABLE 8.3 : Precision of modified loss-on-ignition results on calcareous and silicious Mendip cave sediments (initial sample weights ranged from 4 to 6g and there was no correlation between % loss and initial sample weight).

REPLICATE	WSM W1 S1 (silicious sediment)	WSM W1 S6 (calcareous sediment)
	(% loss)	(% loss)
1	1,48	8,84
2	1,68	9,22
3	1,57	8,98
4	1,50	8,96
5	1,83	9,18
6	1,62	9,21
7	1,50	9,27
8	1,67	8,98
9	1,64	8,88
Mean	1,607	9,058
Standard Deviation	0,111	0,162
Standard Error	0,037	0,054

CHAPTER IX

SOME ASPECTS OF CAVE SEDIMENTOLOGY IN THE MENDIPS DURING THE PLEISTOCENE WITH SPECIAL REFERENCE TO WESTBURY-SUB-MENDIP

The purpose of this chapter is to illustrate a number of points made previously (Chapter VIII), and to present a brief overview of the likely sedimentology events that have occurred in Mendip caves (particularly Westbury-sub-Mendip) during the Pleistocene. It is not intended as a comprehensive review, nor are the discussions of specific sites intended as site reports.

The Lower Pleistocene

As discussed previously (Introduction, Section III) the preservation of many deposits of lower Pleistocene age is unlikely in the Mendip region, although many of the abandoned higher level caves, particularly in western and central Mendips, may have been formed and/or enlarged during the lower Pleistocene. However, the only cave that can be firmly assigned to this period on the basis of its contained deposits is Westbury-sub-Mendip, where quarrying has exposed a large rift chamber of a once extensive system. The thick (10-20m) lower sequence of silicious deposits (Bed 1 of Bishop 1982) have yielded a sparse mammalian fauna of probable lower Pleistocene age (see Chapter VI). The cave deposits were first exposed in 1969 (Heal 1970) and lie between 213m and 244m OD on the southern edge of the limestone plateau surface. Subsequent quarrying removed the southern wall of the chamber to expose a sedimentary sequence approximately 100m long and 30m thick. Solutional lowering of the plateau surface has also largely removed the cave roof so that in a number of places (particularly at the western end) the cave sediments lie just below the modern soil surface.

Unfortunately the deposits have been severely damaged since the work of Bishop (1975,1982) by an attempt to completely remove them with explosives. Thus a unique opportunity has been lost to study vertical and lateral variation on a large scale in cave sediments that span the lower to middle Pleistocene. Fortunately not all the deposits have been destroyed and this work relates to some of those that can still be exposed by excavation (Circa 1986).

At one point in the silicious deposits a fragment of the northern cave wall is exposed within which solutional scallops are preserved. Goodchild & Ford (1971) and Blumberg & Curl (1974) have shown that there is a direct relationship between scallop wavelength and flow characteristics, and a number of studies have used scallops to estimate palaeohydraulic discharge flow velocities and flow directions (Curl 1974, Gale 1984). The scallops at Westbury-sub-Mendip should therefore preserve information on flow conditions during the formation of the cave (presumably the lower Pleistocene). The scallops were measured using the measuring device described by Lauritzen (1981); however their heavily weathered conditions precluded accurate assessment of their wavelength which may be in error of up to ±0.5cm. 23 scallops were measured and their mean wavelength was 5.2±1.0 cm. with a range of between 3.8 to 8.3 cm.

The mean flow velocity in a paralleled wall conduit can be calculated from the scallop wavelength by: (Gale 1984, adapted from Curl 1974)

$u = u* [2.5 \{Log_e(d/2\lambda)-1\}+B_L]$
and
$Re* = u* \lambda px/\mu$

where
u = the mean flow velocity in a parallel walled conduit
u* = the mean boundary shear velocity
λ = the mean scallop wavelength
d = flow depth or distance between conduit walls
B_L = Prandtl's bed roughness coefficient
Re* = stable scallop Reynold's number
Px = fluid density
μ = fluid dynamic viscosity

Blumberg & Curl's (1974) estimates of Re* = 22200 and B_L = 9.4 were used and conduit fluid was assumed to be pure water at 10°C (μ = 0.013cm sec^{-1}). The distance between the conduit walls cannot be measured at Westbury-sub-Mendip since the southern wall has been almost completely removed; but it can be tentatively estimated as 10±5m by extrapolating the line of the remaining sections of the wall (for this reason no estimate of the discharge has been attempted). Table 9.1 shows the likely mean scallop forming conduit flow velocity which is approximately an order of magnitude larger than the mean conduit flow velocity that Atkinson & Smith (1973) have calculated for present day central Mendip caves (D.0852±0.0684 in sec^{-1}, n = 16). However, scallop forming flow velocities have been shown to correspond to flood velocities rather than to the mean annual flow velocity (Pisarowicz & Maslyn 1981, Lauritzen *et al* 1983). Therefore the velocities are comparable with those in present day Mendip caves under flood conditions. It seems more likely that the Westbury-sub-Mendip scallops were formed under a temperate hydraulic regime rather than a nivial flood regime.

By using Gale's (1984) estimate that for scallops of mean wavelength 0.05m the mean boundary shear stress (u) is likely to have been 3.38Nm^{-2}, it is possible to calculate the maximum size of particle likely to have been entrained by these flows, from Bridges' (1981)

TABLE 9.1 : ESTIMATES OF MEAN SCALLOP FORMING VELOCITIES FROM WESTBURY-SUB-MENDIP (All velocities in m/sec^{-1})

Estimated Distance between conduit walls	Velocity for minimum sized scallops (3,8cm)	Velocity for mean sized scallops (5,2±1,0 cm)	Velocity for scallops maximum sized (8,3cm)
5m	1,3	0,91	0,21
10m	1,44	1,01	0,59
15m	1,51	1,06	0,63

least squares polynomial regression equation solution of Miller *et al*'s (1977) data:

$$D = 0.023\tau_c^{\,0.9} : \tau_c > 4.0 \text{ dynes/cm}^2 \text{ and } D > 0.08\text{cm}$$

where D = grain diameter
τ_c = critical bed shear stress.

This yields a value of approximately 5.5mm. However Gale (1984) has calculated that particles of up to a maximum of 0.6m diameter may be moved in suspension on a flow of this size according to the equations of Gibbs *et al* (1971). This is approximately an order of magnitude greater than the maximum size of gravel clasts (0.05m) found in the silicious gravel deposits close to the scallops at Westbury-sub-Mendip. Even allowing for the fact that the work of Gibbs *et al* (1971) is only applicable to spherical particles and that their published equation contains a typographical error which leads to an approximate 22% error in the evaluation of particle radius (Komar 1981); a difference of this size probably means that either the silicious sedimentary fill is not contemporaneous with the scallops or that the maximum size of clasts was supply limited rather than transport limited.

The silicious sediments themselves are indicative of a range of hydraulic environments, well bedded and cross bedded medium and fine sands are present, along with considerable thicknesses (+3m) of interbedded fine sands, silts and clays (laminae approximately 1 to 5mm thick) indicative of a fluctuating flow regime. Gravel lenses are rare and largely consist of granule and pebble size silicious fossils, chert particles and occasionally rolled and stained bone. In places concentric spherical rings of staining are found within the sand which are probably limestone clast ghosts since small pieces of heavily corroded limestone are occasionally found at the centres of the rings. The limestone ghosts probably result from the presence of aggressive conduit waters during the lower Pleistocene. A thorough study of the silicious deposits is however precluded by the difficulty of excavating sections, as the majority of these deposits are now completely buried beneath tonnes of blast rubble.

Silicious fill of this type is unknown from other Mendip cave sites. The source rocks for the Westbury-sub-Mendip fill are the Harptree beds which contain a virtually identical heavy mineral suite (H. Davis *per com*). Of particular note is the presence of limonitic oolites which are distinct from those found in other silicious geological deposits in Somerset, such as the Greensand. The nearest present day exposure of Harptree beds to Westbury-sub-Mendip is around the Devil's Punchbowl, 5km to the north east, where they form part of the present day land surface. However the direction of flow at Westbury-sub-Mendip as determined from the scallops is north west-south east (bearing 98°±11°) which is orthogonal to the present day drainage. This bearing is consistent with the trend of the cave although this is difficult to measure because of the lack of a south wall.

The statistical significance of the scallop bearing data can be tested using the An180 orientation statistics of Dale & Ballantyne (1980) which yields a value of 2.01 which is significant at better than the 1% level (Stephens 1969). A west-east drainage pattern is consistent with the work of Frey (1975) who has argued on the basis of morphometric analysis that the Plio/Pleistocene drainage was predominantly west-east.

If the catchment area of the lower Pleistocene Westbury-sub-Mendip cave did lie to the west, then the Harptree beds must have been much more extensive than the present day exposures (which all lie to the east) would suggest. All the Westbury-sub-Mendip silicious deposits are virtually completely decalcified (0-8ppm, measured by atomic absorption spectroscopy) which is consistent with the idea of surface flow over silicious deposits which would result in aggressive waters. Further support for this idea comes from sediment analysis from the Cheddar caves. Calcareous deposits in both Gough's cave and Sunhole contain a small number of limonitic oolites similar to those found at Westbury-sub-Mendip and in the Harptree Beds (personal observation and S. Colcutt *per com*). The upper reaches of the Cheddar catchment also have a north-west south-east trend at variance to both the present day topography and the Triassic drainage pattern. A north-west south-east drainage pattern would presuppose that the Mendip plateau surface was at a similar altitude to the surrounding countryside, unlike the present day situation where it has an elevation of approximately 250 metres in western and central Mendip.

In conclusion, it seems likely at some time during the lower Pleistocene that

(1) the drainage pattern was north-west south-east;

(2) differential erosion had not yet raised the Mendip plateau surface much above the surrounding countryside;

(3) the Harptree Beds were much more extensive and have subsequently been stripped from west to east, exposing the Carboniferous Limestone plateau;

(4) 'temperate' conditions similar to present day occurred at some point.

The Middle Pleistocene

The only Mendip cave that can be definitely assigned to the mid Pleistocene on the basis of its contained deposits is again Westbury-sub-Mendip (cf Bishop 1982). Mammalian faunas from four other Mendip caves may date from the mid Pleistocene (see Chapter 6); however only limited information can be gained from these caves. The fills at Hutton and Clevedon caves have been virtually completely removed. Most of the sediments in Bleadon cavern have also gone and the present entrance up to the bone chamber is now treacherous.

However some fossiliferous sediments remain in wall alcoves and further work on this site may prove productive in reconstructing the original stratigraphy of the deposits. Banwell bone cave is the only one of these four sites where substantial quantities of fossiliferous sediments remain, despite the fact that hundreds of tonnes of deposit were removed during the last century. It is possible to reconstruct the original stratigraphy based on small sections exposed in wall alcoves and the 'Baker extension'; however no extensive excavation has been attempted since the potential of this site is so large that a major interdisciplinary excavation should be undertaken. Until then the deposits should be left intact. Uranium-series determination on Mendip cave speleothems have yielded a number of mid Pleistocene ages (see Chapter III); however the associated sedimentary fills are generally restricted. The restricted sections in the lower deposits of Sun Hole, Cheddar, have produced a number of broken fragments of the mollusca *Lyrodiscus pilsbury* which is only known in the U.K. from mid Pleistocene molluscan fauna at Hitchin (Ellis 1983). These sediments may therefore date from the mid Pleistocene although the possibility of the reworking of older deposits cannot yet be excluded (Colcutt *per com*). Therefore the discussion of the mid Pleistocene will be confined to the calcareous sediments of Westbury-sub-Mendip where extensive sections are available.,

The large continuous sections described by Bishop (1982, Beds 2-10) have now been destroyed and the remaining deposits are now only exposed in a number of smaller and widely spaced sections. Therefore a primary problem with the Westbury-sub-Mendip calcareous deposits is in reconstructing the original stratigraphy from the sections that remain. This also provides an opportunity to test the concept of Colcutt (1985) that primacy should usually be given to the observable features of sediment rather than to the results of laboratory determinations. Colcutt (1984) has attempted the cross correlation of different sedimentary sections at Pontnewydd cave, using single linkage cluster analysis with a similarity matrix of "Sokal & Sneath's (1963) coefficient of similarity". There are a

TABLE 9.2 : Coding scheme of observed features of Westbury-sub-Mendip sediments

VARIABLE	VARIABLE TYPE	VARIABLE RANGE OR CODED CATEGORIES
Colour (Hue)	Continuous	0-40 (Red = 0-10, Yellow Red = 11-20, Yellow = 21-30, Green-Yellow = 31-40
Colour (Value)	Continuous	0-10
Colour (Chroma)	Continuous	0-20
Bed Thickness	Continuous	0-4.5
Speleothem	Categorical	1 = Absent, 2 = Present
Bed Clarity	Categorical	1 = Discontinuous, 2 = Continuous
Staining	Qualitative	1 = Absent, 2 = Orange, 3 = Black + Orange, 5 = Reddening, 6 = Black + Red,
Texture (Fine Fraction)	Qualitative	1 = Mostly Clay, 2 = Mostly Silt, 3 = Mostly Sand, 4 = Calcitic Silt (rotten speleothem)
Texture (Coarse Fraction)	Ordinal	1 = Absent, 2 = Pebbles, 3 = Pebbles + Cobbles 4 = Pebbles + Cobbles + Boulders
Rock Type	Qualitative	1 = Limestone, 2 = Limestone + Chert, 3 = Chert, 4 = Limestone + Chert + Flint
Clast Shape	Ordinal	1 = Rounded, 2 = Sub-rounded, 3 = Sub-Angular, 4 = Angular
Clast Alteration	Ordinal	1 = Minimal, 2 = Moderate, 3 = Extreme, 4 = Ghosts (completely dissolved)
Bedding (Structure)	Ordinal	1 = None, 2 = Weak, 3 = Strong
Cementation	Ordinal	1 = Absent, 2 = Weak, 3 = Heavy
Bone	Ordinal	1 = Absent, 2 = Trace, 3 = Common

TABLE 9.3 : OBSERVED FEATURES OF WESTBURY-SUB-MENDIP SEDIMENTS USED FOR MULTIVARIATE ANALYSES
(* indicate missing data)

Sediment Unit No.	Munsel Colour Hue	Munsel Colour Value	Munsel Colour Chroma	Bed Thickness	Speleothem	Bed Clarity	Staining	Texture (Fine Fraction)	Texture (Coarse Fraction)	Rock Type	Clast Shape	Clast Alteration	Bedding (Structure)	Cementation	Bone
17/6	15	5	6	****	2	*	5	1	4	1	4	1	1	3	3
18/2	20	4	2	2,27	1	2	4	2	4	1	3	3	1	1	3
18/3	22,5	6	4	2,27	1	2	5	2	4	1	3	2	1	1	3
18/0	22,5	4	4	1,30	1	2	4	2	4	2	2	1	1	1	2
18/1	22,5	4	2	1,30	1	2	2	2	4	2	2	1	1	2	2
19/1	15	5	8	0,24	1	2	4	2	3	1	3	3	1	1	2
19/2	20	6	6	0,96	1	2	4	2	4	2	3	3	1	2	3
19/3	17,5	5	8	0,10	1	2	3	2	3	2	3	3	1	1	2
19/4	22,5	7	6	1,00	2	2	6	2	4	1	3	2	1	3	2
8/4	****	*	*	2,50	1	1	4	2	3	2	1	2	2	2	3
8/5	20	6	6	0,25	1	1	4	2	2	2	2	1	2	1	3
19/5	17,5	5	6	0,45	2	2	3	2	3	2	3	1	1	2	2
19/6	20	6	6	0,25	1	2	6	2	3	4	2	1	1	2	2
19/7	17,5	4	6	0,18	2	1	3	2	3	2	2	3	1	2	2
19/8	10	5,5	5,5	0,30	2	2	4	2	2	4	2	3	1	2	3
19/9	15	5	6	0,16	1	1	4	2	3	4	2	3	1	2	2
19/10	10	6	6	1,20	1	2	5	2	4	4	2	3	2	3	3
19/6-19/10	17,5	4,5	6	1,20	2	1	1	2	4	4	1	3	2	3	2
19/11	16,3	5	7	0,65	1	2	3	2	4	2	2	3	3	1	2
19/12	20	5,5	8	1,20	1	2	5	2	3	2	3	1	2	3	2
20/1	16,2	5	7	3,00	2	2	1	2	4	2	4	1	2	2	2
19/13	15	5	7	1,00	1	2	4	2	4	2	3	2	1	2	2
19/14	12,5	5	6	0,50	1	1	3	2	3	2	3	2	1	3	3
19/15	20	5,5	6	0,60	1	2	4	2	4	2	2	2	1	3	3
19/16	15	5	6	0,50	1	2	4	2	3	2	3	2	2	1	2
19/17	20	5,5	6	0,30	1	2	2	2	4	1	3	2	1	1	2
20/2	13,7	5	6	2,00	2	2	1	2	4	1	4	1	2	1	2
18/6	20	5	3	****	1	2	2	2	3	1	3	1	1	2	3
18/7	15	5	8	0,40	2	2	1	2	4	1	3	1	1	3	2
18/8	16,3	4,5	7	0,30	1	2	6	3	3	1	3	1	2	3	2
1	16,1	5,4	5,5	****	1	2	6	2	1	3	4	1	3	1	1
17	18,7	5	/	2,45	2	2	3	1	4	2	1	3	1	1	1
11/1	15	4	6	0,32	1	2	1	2	4	2	4	1	1	2	3
11/2	17,5	6	6	0,34	2	2	2	4	3	1	4	1	1	3	2
12/1	17,5	4	4	0,34	2	2	1	3	4	1	4	1	1	1	2
11/3	****	*	*	0,10	2	1	3	4	3	1	4	1	1	3	2
11/4	15	4	6	0,70	2	2	2	4	4	1	3	1	1	1	3
14/2	20	4	5	0,25	2	2	4	1	1	*	*	4	1	1	2
12/2	15	3	4	0,50	2	2	3	2	4	2	4	1	1	1	3
15/3	15	4	6	0,42	1	2	1	2	2	3	4	4	1	1	1
15/4	15	4,5	6	0,55	2	2	3	4	2	2	4	4	1	1	2

Sediment Unit No.	Munsel Colour Hue	Value	Chroma	Bed Thickness	Speleothem	Bed Clarity	Staining	Texture (Fine Fraction)	Texture (Coarse Fraction)	Rock Type	Clast Shape	Clast Alteration	Bedding (Structure)	Cementation	Bone
15/5	15	5	6	0,30	1	2	3	1	1	*	*	4	1	1	1
15/6	17,5	6,5	6	0,15	2	2	4	4	2	3	4	4	1	1	1
15/7	16,2	4,5	7	****	1	2	6	1	2	3	4	4	1	1	2
15/8	15	4	6	0,30	2	2	4	3	2	3	3	4	1	1	3
15/9	12,5	4	8	0,60	1	2	4	2	2	3	4	4	1	1	1
1/1	18,7	5,5	7	0,90	1	2	2	1	2	3	3	2	2	2	1
1/2	21,5	6,3	5 5	0,15	1	2	1	3	2	3	4	1	3	1	1
1/3	17,5	5	8	0,60	1	2	2	3	2	3	1	1	2	1	2
1/4	21	5,9	7,5	0,90	1	1	2	3	1	*	*	*	3	1	1
2/1	15	5	8	1,20	2	2	1	2	4	1	4	1	1	2	2
2/2	20	5	4	0,60	2	1	4	2	4	1	3	2	2	1	3
2/3	15	4	6	0,80	1	2	3	1	4	1	4	1	2	1	3
10	18,7	5	7	4,50	1	2	1	3	4	1	3	1	2	2	2
3	15	3	4	0,12	1	2	4	2	3	1	2	1	1	3	1
4	20	5	6	0,30	1	2	1	3	2	1	1	3	2	1	1
13/1	16,3	3,8	5,5	2,15	1	2	1	2	4	2	3	1	1	3	2
14/1	20	5,5	3	0,60	2	1	2	2	4	2	4	2	1	3	3
15/1	15	5	8	0,20	1	2	1	2	4	2	3	1	1	3	3
15/2	12,5	4	6	0,60	2	2	1	2	4	2	3	4	1	1	3
21	15	5	6	****	1	2	2	2	4	1	4	1	1	2	2
5/1	17,5	4	6	****	1	1	1	2	2	1	3	1	1	1	2
5/2	19,2	5,5	7	0,30	1	2	1	2	3	1	4	1	1	1	3
6	12,5	4	8	0,35	1	2	3	2	4	1	4	1	1	1	2
7	17,5	6	8	0,50	1	2	6	1	4	1	4	2	3	1	1

number of methodological flaws in this procedure: firstly single linkage algorithms are unreliable (see Appendix 3), and secondly the use of Sokal & Sneath's similarity coefficient requires that continuous variables are arbitrarily divided up into four categories, a procedure that leads to significant loss of information (Webster 1977). Therefore this procedure is unlikely to yield optimum results (no cluster diagnostics are presented by Colcutt (1984) so the statistical validity of the solutions is impossible to assess).

In order to attempt a cross correlation of the Westbury-sub-Mendip sediment, all the observed features of the sediment were coded using the scheme shown in Table 9.2 (the data is shown in Table 9.3). All these variables were recorded independently by Dr P. Andrews and Dr J. Cook and D. Gordon. Where discrepancies arose the sediments were either re-examined where possible or the observations of D Gordon were given preference. The observational data is mixed, containing both continuous, categorical and qualitative variables (Table 9.2). There are a number of similarity measures that can be used to compare mixed multivariate data, the most widely used being Gower's flexible coefficient (Gower 1971):

$$Sij = \frac{\Sigma_{wijk}}{\Sigma_{zijk}}$$

where Zijk = the value for the comparison for the K^{Th} character

where Wijk = the weight assigned to it

For continuous variables

$$Zijk = \frac{1 - (Xik - Xik)}{^{r}k}$$

where ^{r}k = the range of the character.

It can be shown that when all data are categorical then Gower's flexible coefficient is equivalent to Jaccard's coefficient (see Appendix 3) and when all data are quantitative it is equivalent to mean character distance (also known as Manhatten or city block metric) (Cain & Harrison 1958).

Of the widely available computer packages that support multivariate data analysis only the GENSTAT package has an implementation of Gower's flexible coefficient. Unfortunately it is implemented in a form that only allows cluster analysis to be undertaken using a single linkage algorithm; if categorical variables are included in the data set. There seems to be no obvious reason for this and although it is probably feasible to output the Gower's flexible coefficient matrix from the GENSTAT package and then undertake cluster analysis using a different package (eg CLUSTAN, BMDP), there is no obviously easy way of doing this.

The single linkage cluster solution unsurprisingly failed to produce adequate cluster recovery from the Westbury-sub-Mendip observational sediment data. No similarities between sediment samples were greater than 85% and it seems highly probable that some degree of chaining has occurred, thus preventing optimum recovery using the single linkage method (see Appendix 3). In order to attempt to establish the multivariate relationship between the Westbury-sub-Mendip sediment samples, principle co-ordinate analysis was performed on the Gower's flexible coefficient matrix. Principle co-ordinate analysis is a multivariate ordination technique essentially analogous to principle component analysis but applicable to non-euclidean distances (Gower 1966). This technique has been shown to be accurate at representing multivariate similarities with a wide range of data types (Dunn & Everitt 1982). Unfortunately the results are disappointing (Table 9.4). The first nine latent roots between them only explain 65.5% of the variance despite the fact that considerable variable compaction has occurred; such that the principle co-ordinates are not linearly related to the original 15 variables.

TABLE 9.4 : Westbury-sub-Mendip Observational Sediment Data
Principal Co-ordinate Analysis Results

LATENT ROOT	PERCENTAGE VARIANCE EXPLAINED BY LATENT ROOT
1	12,4
2	10,9
3	8,6
4	7,1
5	6,5
6	5,8
7	5,3
8	4,5
9	4,4
	65,5

LATENT ROOT	VARIABLES WHICH CONTRIBUTE SIGNIFICANTLY TO LATENT ROOT
1	Cementation, Rock Type, Texture (coarse fraction), Bone,
2	Speleothem, Texture (fines), Bone,
3	Speleothem, Staining, Bed Thickness,
4	Texture (coarse fraction), Bone, Texture (fines), Colour (chroma)
5	Bed Clarity, Bed Structure, Bone,
6	Rock type, Clast Shape,
7	Speleothem, Clast Shape, Clast Condition,
8	Rock Type, Colour (hue),
9	Bone, Colour (value),

The reason for this low level of explanation is probably that the 15 observed sediment variables do not have sufficient discriminating ability to allow reliable cross correlation between such complex sedimentary deposits. Further ordination analysis such as non-linear mapping or non-metric multidimensional scaling could be undertaken to confirm this (Gower 1966). The problems of accurately cross-correlating the Westbury-sub-Mendip sediments using the 15 observational variables can be illustrated by studying the results from the deposits at two closely spaced sedimentary sequences (W1 and W10).

The W1 and W10 section (Figures 9.1 and 9.2) are approximately 25 metres apart and their deposits are undoubtedly related to each other since the continuous section studied by Bishop (1982) spanned this area of the cave (Stanton 1974).

Although Bishop's sampling from Beds 2-10 was from sediments closer to the centre of the chamber than the present W1 and W10 sections (W Stanton *per com*); some resemblance to the general stratigraphy of Bishop (1982) can be expected even though detailed differences are probable, due to lateral sediment variation, particularly near the cave wall. Therefore there are *a priori* reasons for expecting cross correlations to exist between the W1 and W10 sedimentary sequences. However the idea that these cross correlations can be adequately achieved on the basis of only observational data is unproven. In order to test this hypothesis the first nine principle co-ordinates of the 15 observational variables from the W1 and W10 sediments were plotted as Chernoff's faces (Figure 9.3). Although these 'cartoon faces' 'look silly' they are probably the most effective way of graphically representing variation in nine dimensional space (Chernoff 1973, Everitt & Nicholls 1975, Everitt 1978). For obvious 'biological reasons' human beings are extremely efficient at detecting even small variations in facial expression (even with cartoon faces) whereas they are inefficient at detecting small numerical changes in the values of large tables (A. MacDonald *per*

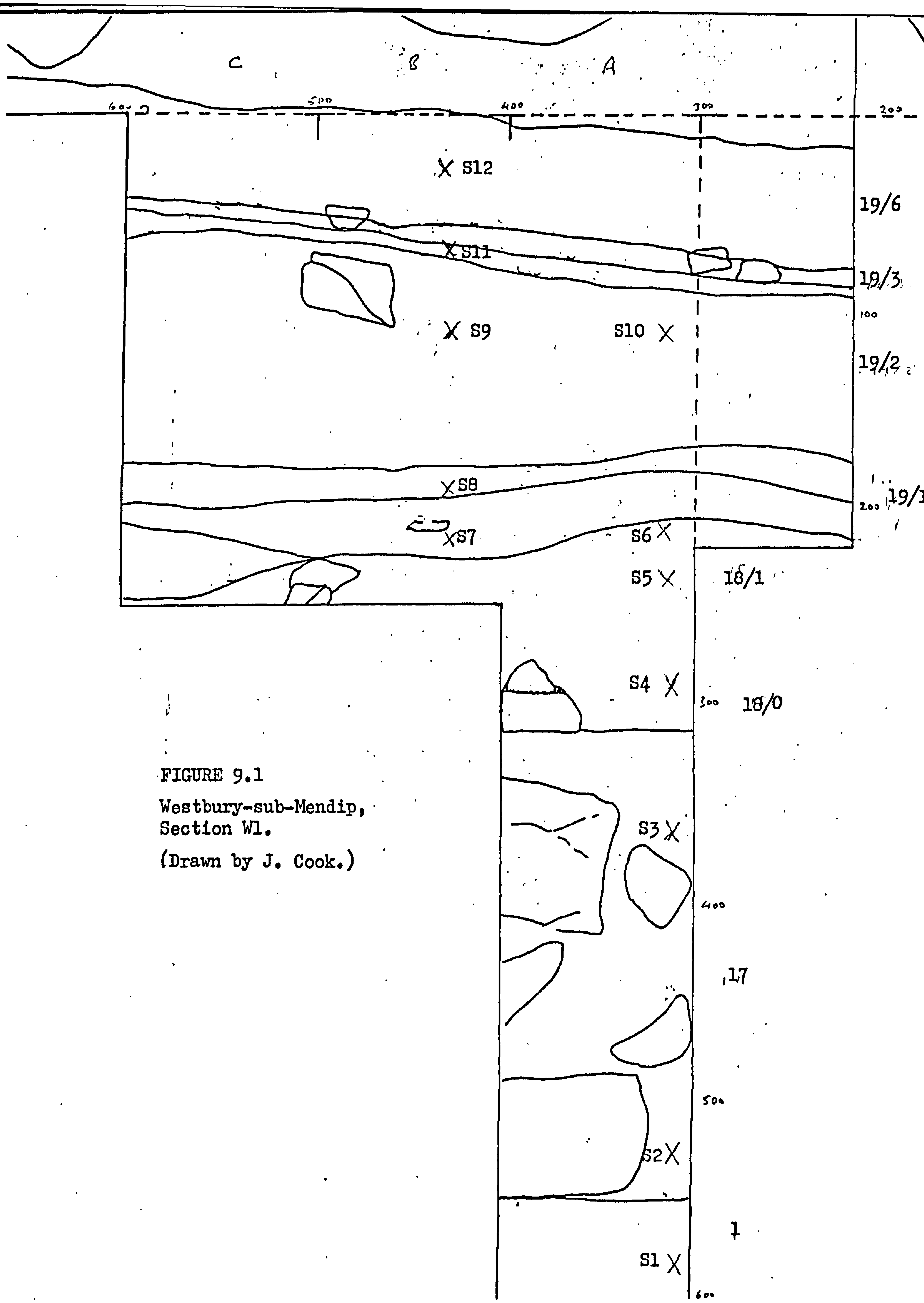


FIGURE 9.1

Westbury-sub-Mendip,
Section W1.

(Drawn by J. Cook.)

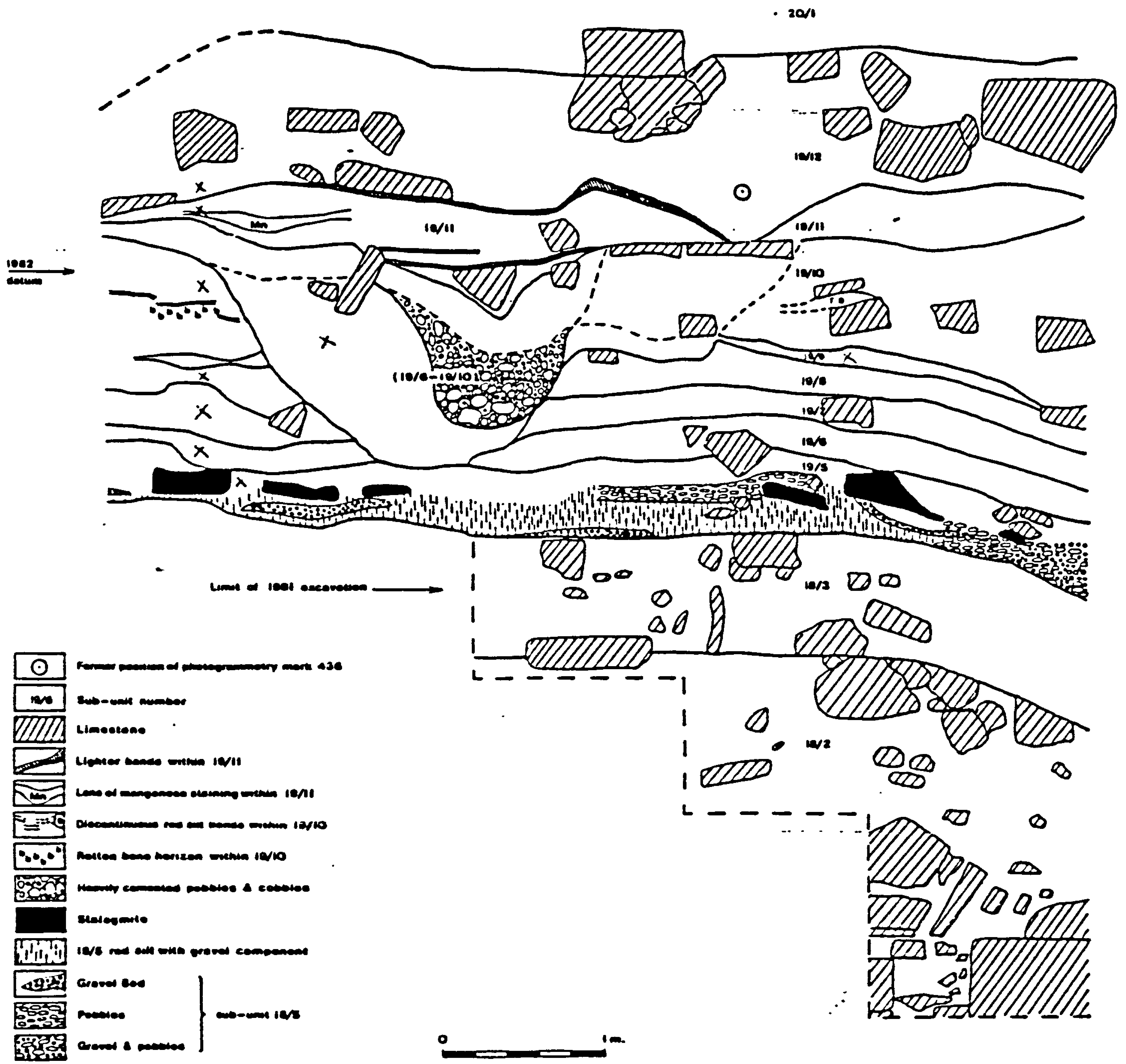


FIGURE 9.2

Westbury-sub-Mendip, Section W10.

(Drawn by J. Cook.)

com). The nine principle co-ordinates are represented by variation in nine features of the cartoon faces such that: (Frith 1974):

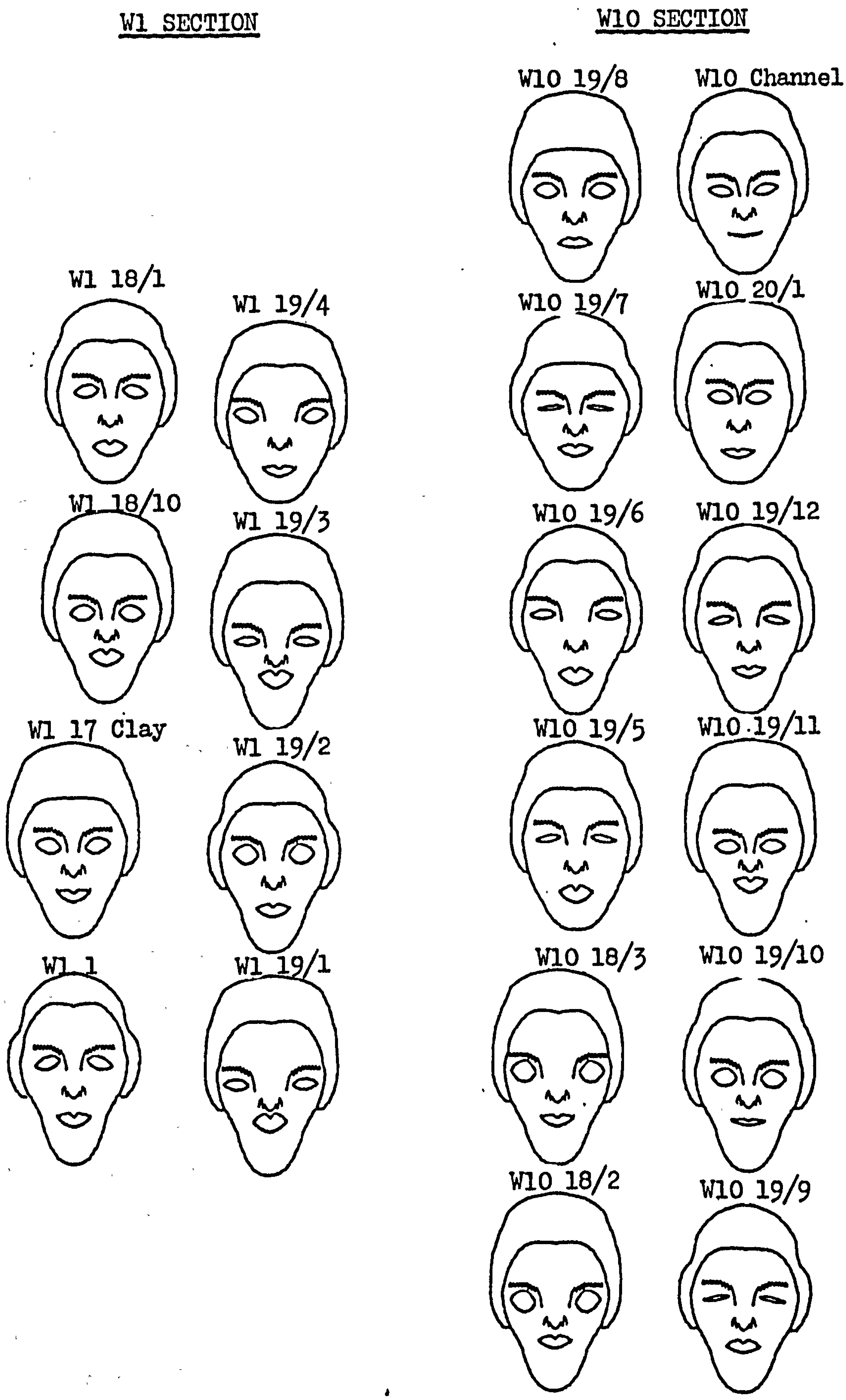
1) Upper hair = first principle co-ordinate
2) Chin curves = second principle co-ordinate
3) Lower hair = third principle co-ordinate
4) Eye size = fourth principle co-ordinate
5) Mouth size = fifth principle co-ordinate
6) Eye brow separation = sixth principle co-ordinate
7) Eye slant = seventh principle co-ordinate
8) Mouth curve = eighth principle co-ordinate
9) Feature compaction (eye to mouth space) = ninth principle co-ordinate

Although the 'visibility' of changes in these nine features varies (Frith 1974) (eg mouth curve is more visible with a thin mouth size than with a thick mouth size), they accurately represent variation in the nine principle co-ordinates such that similar deposits will be depicted as similar cartoon faces. However examination of Figure 9.3 shows the difficulty in attempting cross correlation on the basis of just observational data. No obvious matches are apparent even though cross correlation can be expected. Therefore observational data alone has in this case proved insufficient to enable accurate sediment matching, thus emphasising the need for laboratory analysis to be undertaken in conjunction with observation in the study of cave sediments (contra Colcutt 1985).

<u>Weathering of Cave Sediments and Climatic Variation</u>

The W1 section (Figure 9.2) at Westbury-sub-Mendip is the only remaining place where the entire sedimentary sequence (from the top of the silicious to the top of the calcareous sediments) can be safely exposed in a single section. Laboratory analysis on these sediments has detected variation in organic carbon, calcium, global particle size, clay content and clast shape. Variations of these

FIGURE 9.3 : Chernoff's faces of the first 9 principal co-ordinators from the sediment observational data from the W1 and W10 sections at Westbury-sub-Mendip.

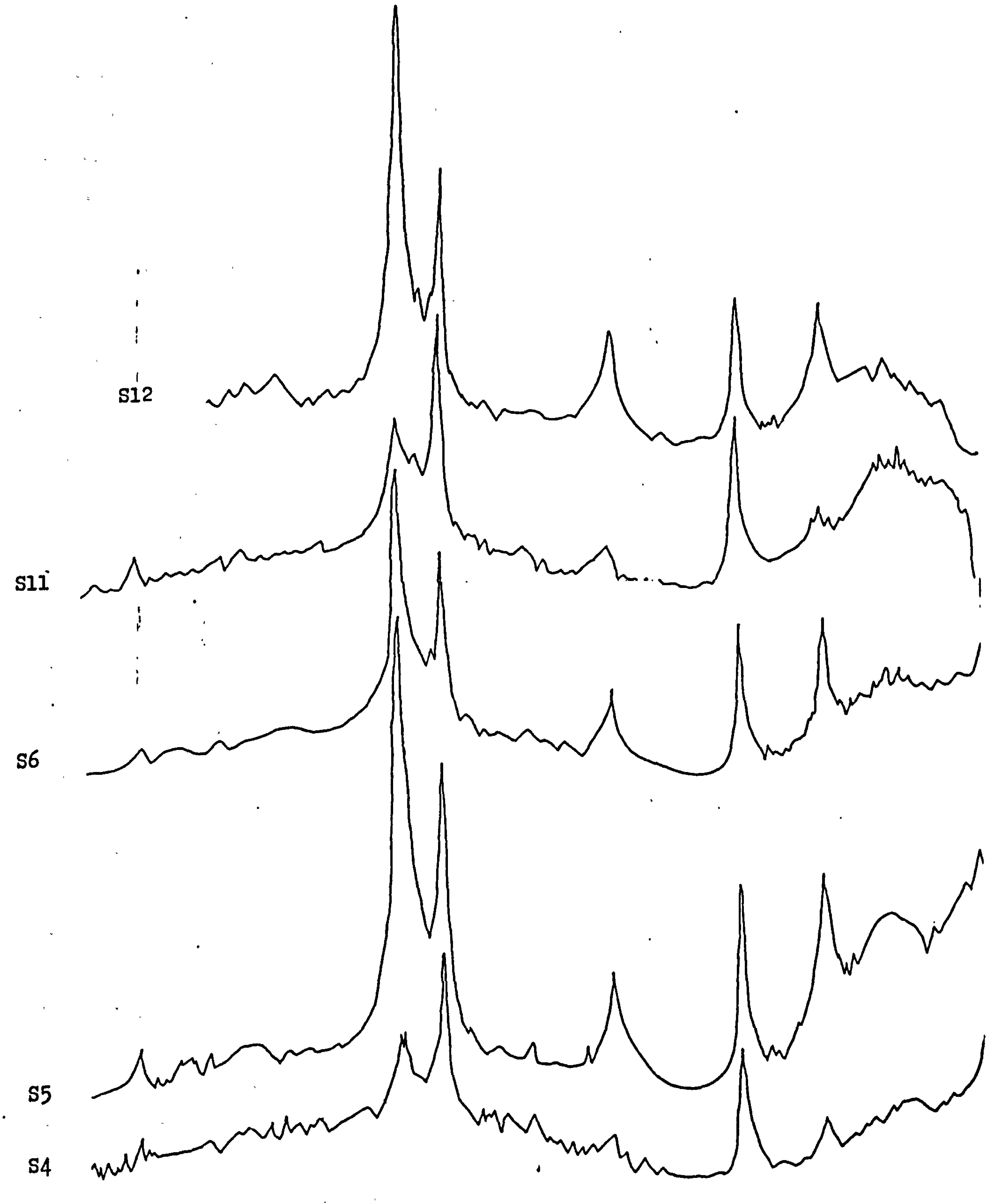


parameters have often been taken by others to be indicative of a sedimentological response to climatic variation (see Chapter VIII). For example, Schmid (1967) studied sediments from three sedimentary layers (A,B and C) at Geula Cave, Mount Carmel, Israel, using techniques developed from middle European cave studies (the German school). Layer A was characterised by "*a great amount of fresh and angular limestone. Fragments of bone are rare*", whereas layers B and C were characterised by *"corroded and rounded"* limestone and numerous fragments of bone. Calcium carbonate and coarse sediment content were greater in layer A than B or C, and Schmid (1967) interpreted these data to mean that layers B and C were deposited under a *"warm climate"* with active chemical weathering, and layer A was deposited under a *"humid but cold climate"* with active frost weathering. Schmid (1967) concluded *"From layer C to B and A we recognise the transition from warm climate - interglacial or inter stadial - to a glacial-like climate"*.

While the sedimentological variation described by Schmid (1967) may well result from differential weathering he presents no evidence that directly links this weathering to climatic variation. The sedimentological variations in the W1 deposits at Westbury-sub-Mendip also probably result from differential weathering. XRD analysis of the clay content of the W1 sediments (Figure 9.4) shows that there are probably differences in the proportions of mixed layer clays and illites between the deposits. The degree of clast rounding also varies between the W1 deposits (see Appendix 6). Clast rounding can be directly related to weathering since sectioned clasts show marked weathering rinds up to 4mm thick and complete clasts surrounded by exfoliated 'skins' can be found intact in the W1 deposits, particularly in the vicinities of sample 6 and 7.

Although these weathering differences within the W1 section could be interpreted in terms of climatic variation there is little direct evidence of this. An alternative source could be variations in the amount and degree of biological weathering. The upper deposits in the W1 sequence (18/0-19/4) were formed during occupation of the cave

FIGURE 9.4 : XRD analysis of the clay fraction from samples 4,5,6,11 and 12, Section W1, Westbury-sub-Mendip.



by bears *(Ursus deningeri)*, and large quantities of bear bones have been recovered from these sediments (A Currant *per com*). Uric acid in bear faeces, urine and perspiration is corrosive to limestone sediments as are the organic acids released during cadaver decomposition. Therefore the presence of a large number of mammals living and dying within a cave could potentially cause greater amounts of weathering than temperature changes. To test if biological weathering has significantly affected the W1 sediments, phosphate determinations were made on the weathering rinds of clasts (Table 9.5), using standard continuous analysis techniques (Hesse 1971). The phosphate content of the clast weathering rinds are similar to that of pure bone, whereas limestone from the inside of the clast contains no phosphate. This implies that the exfoliation rounding observed on clasts results from expansion caused by the chemical alteration of calcium carbonate to calcium phosphate. Likewise the production of fine sediments and partial decalcification can be attributed to the corrosive effects of mammalian excretions. It seems likely that these biological effects are probably large enough to have swamped the climatically influenced weathering signal. If this is correct it calls into question the climatic interpretations of weathering variations in cave sediments, particularly where the weathered horizons are fossiliferous and the unweathered horizons are sterile (cf. Schmid 1967).

The Upper Pleistocene

Although there are no upper Pleistocene sediments at Westbury-sub-Mendip, the majority of Mendip caves contain sediment of this age. Unfortunately no major sedimentary horizons can yet be firmly correlated with the last inter-glacial complex (the Milton Hill and Durdham Down sites have been completely quarried away). Most Mendip caves contain mainly Devensian and Holocene deposits and active sedimentation is still occurring in many of them. Colcutt (1985) has described the mass movement processes that are the predominant mode of sedimentation in abandoned caves. However with a few notable

TABLE 9.5 : Phosphate Content of Westbury-sub-Mendip Deposits
<u>(initial sample size = 2g)</u>

DEPOSIT	PHOSPHATE CONTENT (Mg/ML)
Fresh Limestone	0
W1 S2 (Silicious)	0
W1 S2 (Clay)	0
'White' weathering rind on limestone clast in W1 S5	54
'White' weathering rind on limestone clast in W1 S6	55
Limestone from inside of clast above	0
Bone in W1 S6	62
<2mm Sediment from W1 S7	58
'Red'weathering rind on limestone clastW1 S8	24
'Red/White' weathering rind on limestone clast from W1 S12	20

exceptions (eg Collier and Flint 1964, Bull 1976, Gale 1981), there are few descriptions of the gravel deposits which form the bulk of sediments in swallet caves. Mendip cave gravels are typically matrix rich with a poorly sorted silty matrix, although a multi modal grain size distribution is common. They are generally unbedded or crudely horizontally bedded with only one fining upwards sequence being present. The clasts are mainly well rounded limestone with both clast and matrix supported gravel being found. There is often little evidence of imbrication except near the cave walls where chaotic orientations are common due to the distorted flowlines. Few deposits show much evidence of reworking during the falling stage.

Gravels of similar natures are known from Devensian surface fluvial deposits and have been interpreted as resulting from an arctic nivial discharge regime where channels are active only during spring melt and dry during summer months (Bryant 1983a,b, Macklin 1985). However caution should be exercised before interpreting cave gravels in these climatic terms, since major flood events routed through a cave will result in aggregation of matrix rich unbedded gravels if sufficient source materials are available. (Similar gravel deposits can be found in tropical Tongan caves, which probably result from hurricane flood events.) Therefore an understanding of the geomorphology of the cave catchment area is necessary before a climatic interpretation is made from cave gravel deposits.

In conclusion a number of points have been noted in the preceding two chapters:

1) Cave sedimentological studies are still in their infancy and have been largely confined to fossil deposits. Little work has been undertaken on present day sedimentation in caves and until such studies are undertaken much cave sedimentology will remain largely conjectural.

2) Observational studies on the morphology of cave sediments will continue to provide evidence of process; however laboratory analysis is often required to solve specific problems.

3) Some laboratory techniques developed for the study of surface sediments are not directly applicable to cave sediments, although they can often be modified.

4) Laboratory studies are extremely time-consuming and should not be used as exploratory tools. Unless laboratory analyses are used to answer specific problems, much of the data generated will remain meaningless facts.

5) Many cave sedimentological studies have interpreted sediment variation in direct climatic terms; however a climatic interpretation may be unwarranted unless other controlling factors (such as biological weathering) can be tested for and excluded.

CHAPTER X

CONCLUSIONS

The purpose of this chapter is to attempt an integration of the Mendip region absolute dated faunal and sediment records. This integration is possibly premature since the current state of knowledge is still extremely sparse. Therefore any synthesis will invariably contain significant errors, particularly of omission. However, a synthesis can be of value in order to define the current state of knowledge of the Pleistocene of the Mendip region. It must be stressed that this is a debatable point since it is arguable that our knowledge of the Mendip region absolute dated faunal and sediment records is so limited that any synthesis will be largely conjectural and, therefore, less rather than greater than the sum of the parts. The dangers of premature synthesis are all too evident from the history of geomorphology and Quaternary science.

In geomorphology first the 'cycle or erosion' theories of Davies and later the denudation chronological approach of Wooldridge and Linton (1955) often became elevated to the level of dogma, which often stifled and impeded rather than advanced the science (although it must be stressed that this was not the intention of the original authors). Likewise, in British Quaternary science, the four cycle 'Alpine' glacial stratigraphy of Penck and Brückner (1909) and later the seven stage glacial/interglacial stratigraphy of Mitchell *et al* (1973) have arguably often hindered the advancement of the subject (although again this was not the fault of the original authors).

This chapter should therefore not be considered a full or correct account of the Pleistocene of the Mendip region but simply a summary of the current state of knowledge. As new information becomes available, significant modifications are to be expected.

The Lower Pleistocene

During the Pliocene it is probable that most or all of the Mendip Hills remained buried beneath a covering of Mesozoic rocks. Towards the end of the Pliocene/beginning of the Pleistocene, erosion exposed the western end of the hills and the Mesozoic cover has since been progressively stripped from west to east predominantly by scarp retreat.

The formation of Westbury-sub-Mendip cave provides evidence for active karstification during the lower Pleistocene. Evidence from scallops at Westbury-sub-Mendip and from morphometric analyses (Frey 1975) indicates a predominant west/east drainage pattern, which suggests that the central Mendip region was not significantly higher than the surrounding landscape (the present plateau surface is approximately 90 metres above the surrounding landscape), and that if the Bristol Channel had formed, the watershed had not yet extended as far as central Mendip (unlike the present day).

The evidence from the silicious fill at Westbury-sub-Mendip indicates that cave formation was occurring whilst significant areas of western Mendip still retained a cover of Harptree Beds. The nature of the silicious fill suggests a low discharge hydraulic regime with fluctuating flow levels. There are no 'flood' deposits present that could be associated with 'periglacial snow melt' conditions. The vertebrate fauna evidence is also indicative of 'mild' interglacial conditions with slow moving rivers (Bishop 1982).

The Middle Pleistocene

The lower Pleistocene silicious fill at Westbury-sub-Mendip is overlain by several metres of fine silty clays of the 'break down zone', which underlie the fossiliferous calcareous deposits (Bishop 1982). The faunal and sedimentological evidence from the calcareous deposits is indicative of at least one and possibly two early middle Pleistocene interglacials, with temperate forest vegetation and conditions at least as warm as the present day; these deposits are probably post Cromerian but pre-Hoxnian in age. (This work and A.P. Currant *per com.*)

The sharp angular boundary between the silicious fill and the 'breakdown' zone probably results from erosion of the silicious fill followed by abandonment of the cave. The breakdown zone fine silty clays were possibly deposited as a thicksotropic mud that often results when flood waters back up into a chamber from lower level active cave passage. Therefore a considerable hiatus probably exists between the fossiliferous lower Pleistocene and middle Pleistocene deposits at Westbury-sub-Mendip. The abandonment of the cave is indicative of at least a local lowering in base level which may have resulted from erosion causing significant elevation of the Mendips above the surrounding landscape. If this is correct, then the drainage pattern would have altered from its west/east pattern to something closer to the present day pattern, ie by the initiation of Cheddar Gorge and the re-excavation of the Triassic valleys in west and north Mendip.

The higher level caves in western Mendip (eg Banwell, Hutton) may also have been abandoned during this period. These caves had certainly been abandoned by the time the mid-Pleistocene cold steppe faunas were deposited in them. These faunas are still poorly understood in the British Pleistocene, but they appear to date from one of the few periods of true steppe or wooded steppe environments; possibly with continental climatic conditions. These faunas are likely to be post-Hoxnian but pre-Ipswichian in age and are possibly between 150000 and 225000 years old; although the precision of the available uranium series dates is poor.

The Upper Pleistocene (The Ipswichian Complex)

The Upper Pleistocene record is much more detailed than those of the lower and middle Pleistocene. The UK speleothem growth record indicates the presence of three periods of increased speleothem growth between 140000 and 80000 years BP (eg IP1 90500 years BP, IP2 105000 years BP and IP3 124000 years BP). These three peaks can be correlated with vertebrate and molluscan faunas indicative of interglacial conditions at several UK sites. Only two corresponding speleothem growth peaks can be identified from the Mendip region record (Men 6 95000 years BP and Men 7 123000 years BP). However, the absence of a 105000 year BP peak probably results from sampling error due to the small sample size, since there is evidence of speleothem deposition *circa*. 105000 years BP in several Mendip caves (eg GB Cave, Sun Hole, Swildon's Hole and Bleadon Cavern). Therefore it seems likely that the Mendip region experienced interglacial climatic conditions at least three times during the upper Pleistocene.

Cluster analysis of the upper Pleistocene interglacial cave faunas indicated that the two Mendip region faunas from Milton Hill and Durdham Down are probably both of IP3 (124000 years BP) age; despite the fact that they have few species in common. The two faunas are indicative of a mosaic of habitats with mature open deciduous and/or mixed woodland areas of open plains or grassland and fairly large rivers. The differences between the two faunas may be largely due to taphonomic factors.

The association of speleothem growth peaks with 'warm vegetated' environments is strengthened by their correlation with Milankovitch insolation peaks as defined by Mörner (1972). A good correlation also exists between the UK and Mendip Region speleothem growth records and coral reef growth in tropical and sub-tropical regions of the world. The association of coral reef growth with relatively high sea levels indicates that upper Pleistocene sea levels may have been close to present day heights on three occasion in some regions of the world. This could account for the often confusing picture that has emerged from studies of raised beach deposits and wave cut platforms in the Mendip region and elsewhere in south west Britain. Mathematical modelling of the sea level changes likely to have been experienced in the Mendip region during the 'Ipswichian complex' may prove useful in helping to unravel the sea level record.

The Upper Pleistocene (The Devensian)

Very few sedimentary horizons of Ipswichian complex age have been preserved in the Mendip region. This contrasts strongly with the large number and thickness of Devensian deposits which are found in many caves and surface exposures. Devensian deposits are generally characterised by the large amounts of sediment transported, although the nature of the transport mechanism often varies. Swallet caves frequently contain fills of matrix rich, unbedded or crudely bedded gravels which are sometimes interspersed with speleothem deposits. Gravel transport and aggredation of this nature has often been associated with periglacial hydraulic regimes, and the presence of interbedded speleothems attests that several such 'cold' periods have occurred during the Devensian separated by periods of 'warmer' climatic conditions. The abandoned caves characteristically contain poorly sorted matrix rich breccias which have probably been emplaced as debris flows. These deposits are again sometimes interbedded with speleothem which is indicative of reduced sediment transport and possibly 'warmer' climatic conditions. Although long Devensian sedimentary sequences are known from several caves (eg Sun Hole, Soldiers Hole, GB Cave), it is unlikely that any one site contains a complete record.

The composite record of speleothem growth in the Mendip region indicates 5 periods of increased deposition between 20000 years BP and 80000 years BP (Men 1 29000 years BP, Men 2 36000 years BP, Men 3 47000 years BP, Men 4 57500 years BP and Men 5 72000 years BP). This record correlates well with the UK record as a whole, although the presence of a 50000 year BP (Dev 4) peak is probably obscured in the Mendip record by the intense sampling of the 57000 year old speleothems in GB Cave. These six periods of speleothem growth probably correspond with interstadial conditions and much of the large mammal fauna typically thought of as mid Devensian may date exclusively from these interstadials, particularly since palaeoecological reconstruction of these faunas indicates a cold, seasonal climate in which snow had cleared by May and probably did not exceed half a metre in depth. In summer unfrozen lakes and pools existed and if permafrost was present it was at depth. There was a nutritious and plentiful diverse mosaic of plant communities, predominantly grasses, but with areas of heather as well as tall vegetation of woody shrubs and possibly trees. The heather moorland could have been confined to the acidic Old Red Sandstone core of the Mendip Hills, with the herb rich grasslands concentrated on the base rich limestone flanks. Areas of tall scrub and/or woodland could have grown in the sheltered valleys and gorges.

In contrast, the Devensian stadial faunas appear to be characterised by a sparse fauna of extremely hardy species such as Musk Ox and Reindeer, which are indicative of arctic conditions. The late glacial mammalian faunas, although abundant, present a confusing picture and it seems likely that they may be composite with significant interstadial and stadial faunas intermixed. The sediments they are associated with are generally similar to Devensian deposits with both debris flows and gravels being attributable to a post Dimlington stadial but pre-Holocene period. However there is some evidence that late glacial sediment transport may have been supply limited compared with Devensian deposits (Macklin *per com*).

Conclusions

To conclude, the absolute dated faunal and sediment records of the Pleistocene of the Mendip region demonstrate that considerable climatic and geomorphological changes have occurred in the Mendip Hills. The large scale climatic changes can be shown to have radically affected the geomorphology and faunal composition of the Mendip region. Furthermore these climatic changes were not parochial events confined to the Mendip region but had a global scale.

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APPENDIX 1

URANIUM- SERIES DATING

The $^{230}Th/^{234}U$ method is the commonest way of dating carbonates. It is based upon the assumption that uranium is co-precipitated with calcite from seepage waters that are free of thorium. This assumption is likely because of the geochemical behaviour of uranium and thorium isotopes. Uranium in the 6+ state is readily soluble as an uranyl ion
UO_2^{2+} which will readily form anion complexes in seepage water with carbonate ions. Thorium by contrast is relatively insoluble and is strongly adsorbed by clay minerals. Assuming speleothems are free of thorium at the time of deposition their age can be calculated from the amount of ^{230}Th to ^{234}U which progressively increases until equilibrium is achieved. However the ratio of ^{234}U to ^{238}U must also be measured, as ^{234}U is constantly being produced from the decay of ^{238}U (Figure A1.1).

Analytical Methods

The $^{234}U/^{238}U$ and $^{230}Th/^{234}U$ activity ratios are normally measured from the alpha particle energies of these isotopes by means of alpha-spectrometry. In order accurately to measure these alpha particle energies it is necessary to purify and separate the uranium and thorium from the carbonate speleothem. The chemical purification technique used on most of the Mendip speleothem samples is identical or essentially similar to that of Kamali (1980) (Figure A.1.2).

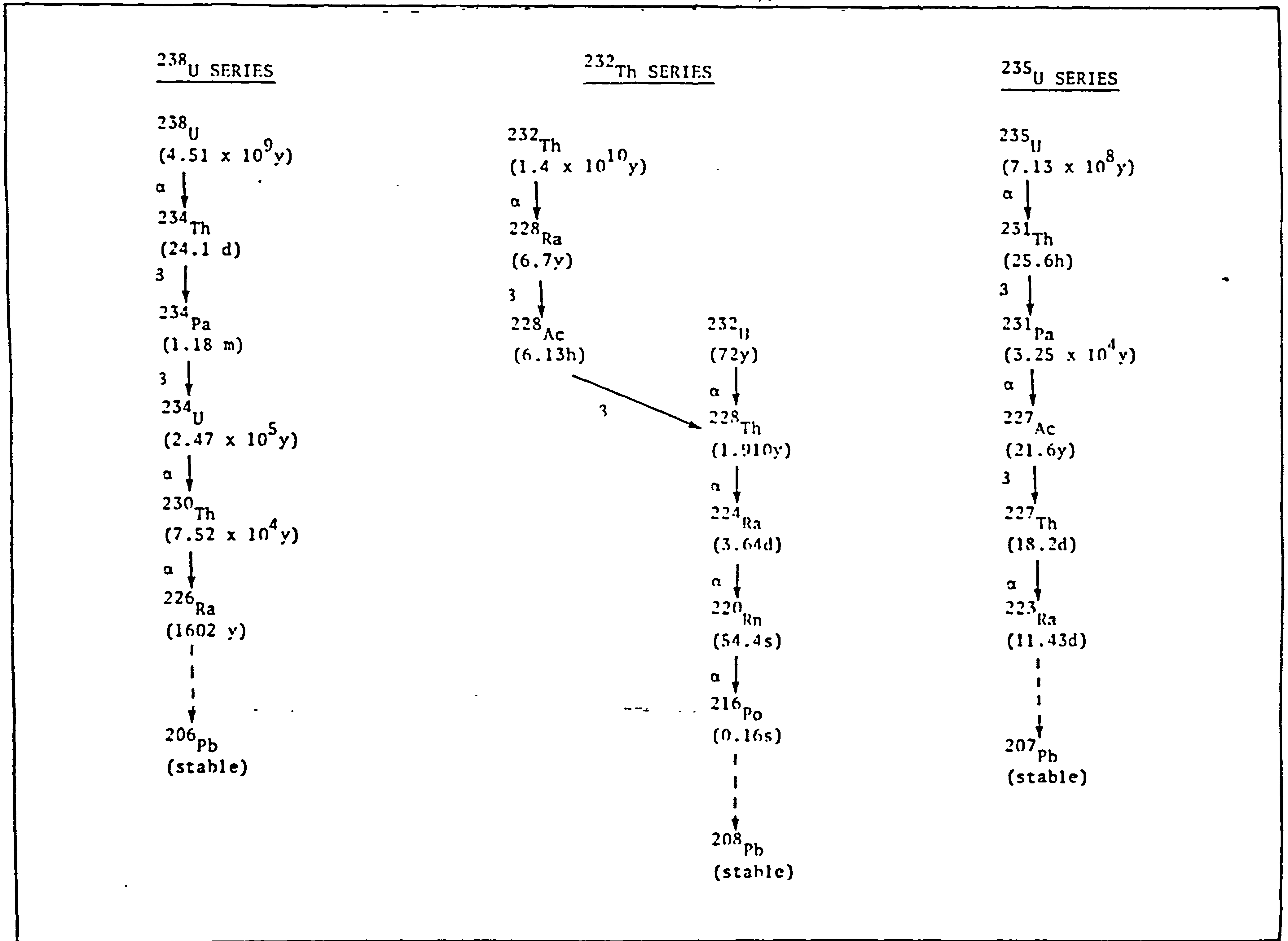

FIGURE A1.1 :
Uranium and thorium decay series, indicating mode of decay and half-life for the nuclides of the respective decay series. (Harmon et al 1975)

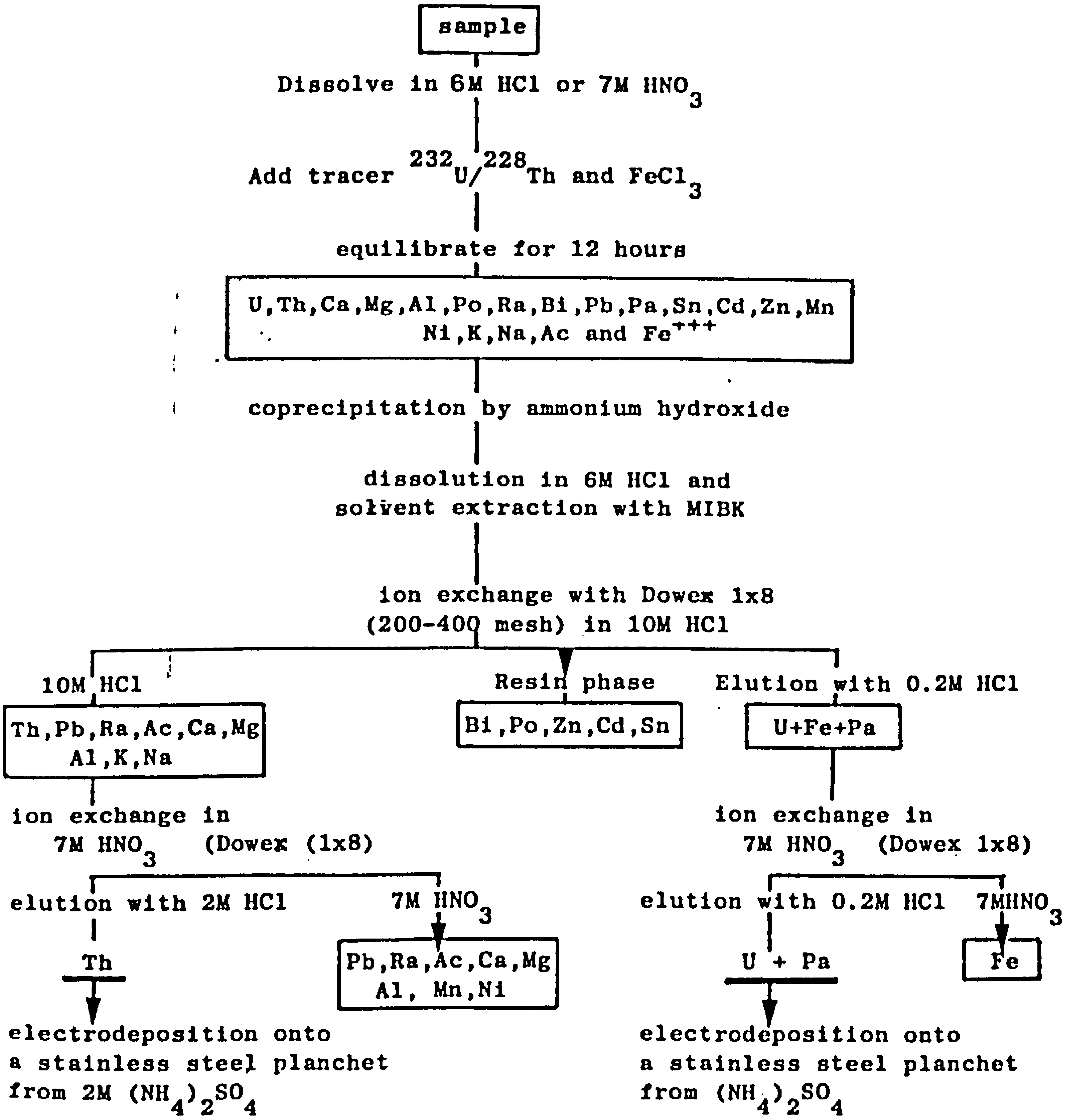

FIG. A.1.2 FLOW SHEET FOR U AND TH ANALYSIS IN CARBONATE ROCKS
(Kameli 1980)

This method can be routinely carried out in an ordinary laboratory and generally gives yields for both uranium and thorium of 70-90%.

The greatest source of loss of isotopes probably occurs during the electro-deposition phase (Kameli 1980), although recently improved electro-deposition methods have been proposed (Hallstadius 1984). Most laboratories have also abandoned the use of the $^{232}U/^{228}Th$ tracer in favour of the $^{236}U/^{229}Th$ tracer which has the advantages of having negligible decay loss because of the long half-lives of these isotopes minimalising recoil contamination to surface barrier detectors and reduced interference from ^{228}Ra alpha decay (Rosholt 1984).

Most of the analytical problems associated with $^{230}Th/^{234}U$ method are now well understood (Bland 1984; de Regge & Boden 1984; Lalley & Glover 1984). A number of the older analyses undertaken during the late 1960s and early 1970s (before the adoption of these modern techniques) should be treated with some caution (Harmon *et al* 1979; P Smart *pers comm*).

The major source of error unaccounted for in the $^{230}Th/^{234}U$ dating methods relates to the partition constant of ^{228}RA and the accuracy of the ^{230}Th and ^{234}U half-lives. The partition constant of ^{228}RA is generally assumed to be 5.5%, which is the proportion of ^{228}RA particles which are assumed to have equivalent alpha energies to ^{228}Th alpha particles. The mean half life of ^{230}Th is usually taken as 108500 years (Attree *et al* 1962) and of ^{234}U as 357800 (Fleming *et al* 1952). More recently these half-lives have been redetermined as 108750±425 years for ^{230}Th and 352740±355 for ^{234}U (Londsbury & Durham 1971; Meadows *et al* 1980). The revision of these half-lives means that if consistent and highly accurate ages are required then quoted dates should be recalculated using these newer half-lives. If more detailed statistical analysis is undertaken on the UK speleothem data it would probably be advisable to recalculate all age determination where enough published data is available to do this. However the size of these errors is probably relatively small: the accuracy of the $^{230}Th/^{234}U$ method in dating speleothems in absolute years can be tested by comparing $^{230}Th/^{234}U$ dates with $^{231}Pa/^{235}U$ dates on the same material $^{231}PA/^{235}U$ dates are independent of $^{230}Th/^{2354}U$ dates as they are based on the ^{235}U decay series (Figure A1.1)

Figure A1.3 shows the mean age of 24 protactinium and uranium-thorium dates in tropical corals quoted by Ku (1968), James *et al* (1971) and Moore & Somayajulu (1974), although these ages all have statistical uncertainties which are not shown. If both $^{231}Pa/^{235}U$ and $^{230}Th/^{234}U$ ages are accurate then it would be expected that their means should cluster about a line of slope 1 in a normal distribution (eg the central tendency). The least squares regression equation for this data is $^{231}Pa = -5732 + 1.01\ U/Th$ with an R^2 adjusted for degrees of freedom of 88%. Although this data set is too small to yield highly reliable results, the regression analysis does indicate that there are unlikely to be any serious errors in either dating technique, unless they are of the same direction and magnitude in both techniques.

Uranium-series Dating of Peat

Uranium thorium analyses have been carried out on two samples of Mosdale 248 peat from the Mosdale interstadial site (Boardman *et al* 1981). The first sample consisted entirely of wood within the peat and the second was a bulk sample containing a wood and peat mixture. The results are shown in Table A1.1. The standard purification procedure followed (Kameli 1980) with the exception that the samples were first ignited in a furnace at 500°C for 24 hours in order to remove organic matter and then leached in 6 molar HCL for a further 24 hours in order to extract the uranium and thorium. The possibility of uranium-series dating peat bog material was considered by Cherdyntsev (1971) as *especially attractive, since uranium may be expected on theoretical grounds to be firmly bound by organic compounds and form a closed system."* Cherdyntsev (1971) found a

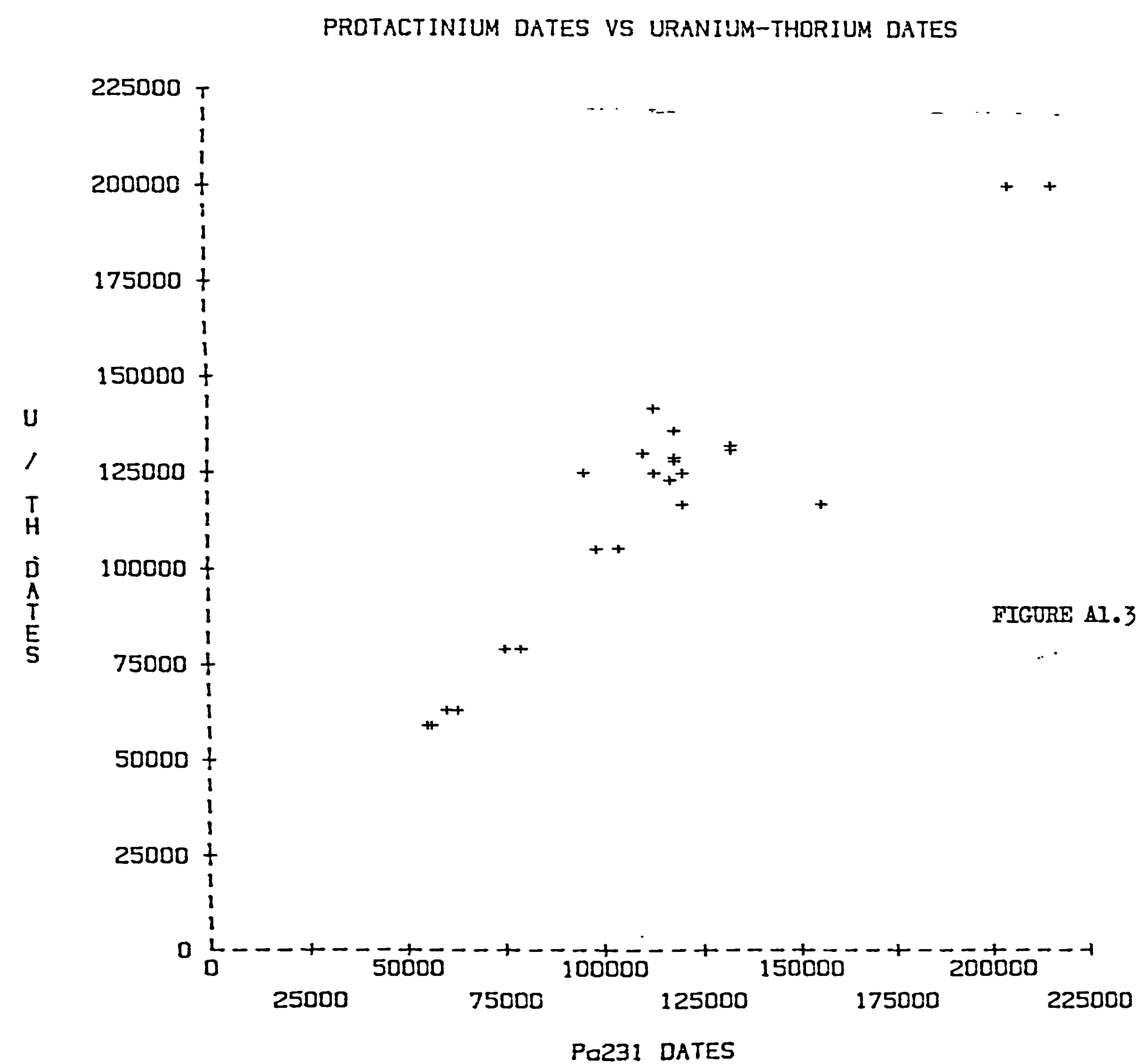

FIGURE A1.3 : Protoactinuim dates Vs uranium-thorium dates on tropical corals.

TABLE A1,1 ; RADIOISOTOPE ANALYSIS OF MOSEDALE PEAT

Sample No,	$^{234}U/^{238}U$	$^{230}Th/^{238}U$	$^{230}Th/^{232}U$	Age (Ky) corrected	Age (Ky) uncorrected	U conc P,P,M
6524 (Wood)	1,980±0,051	1,187±0,102	16	77^{+13}_{-11}	90^{+17}_{-13}	1,658
6525 (bulk peat)	2,133±0,037	1,350±0,112	25	91^{+15}_{-12}	97^{+16}_{-13}	13,100*

good agreement between uranium series and C14 dates from Holocene wood peat in the Kirovo region (USSR). More recently Vogel and Kronfield (1980) have shown close agreement between uranium series and C14 dates in Devensian peat deposits from European sites. However, despite these papers our knowledge of the geochemistry of uranium and thorium in peat deposits is still at a rudimentary stage, as is our knowledge of the chemical problems involved in the purification techniques in dealing with deposits of this nature. Therefore, all uranium-series dates on peat should be regarded as preliminary only until further research has been carried out on the radio geochemistry of modern peat deposits. It may one day be possible directly to calibrate the carbon 14 timescale by comparing uranium-series dates with C14 dates on peat.

Uranium-Series Dating and Mass Spectrometry

Recently uranium-series dating methodology has been significantly advanced by the development of a routine technique for directly measuring the ^{234}U and ^{230}Th content of a sample by isotope dilution mass spectrometry (Chen *et al* 1986, Edwards *et al* 1987). The direct measurement of ^{234}U and ^{230}Th allows significantly smaller sample sizes to be used and greatly increases the precision of uranium-series dating. Edwards *et al* (1987) were able to obtain a precision of just ±1100 years for 1231000 years old coral using only 250mg of sample.

Attempts at mass spectrometric measurements of uranium and thorium isotopes have a long history. Ronan *et al* (1956) were among the first to determine uranium contents of sea water and Tilton & Aldrich (1954) were among the first to determine thorium from rock samples. Rosholt *et al* (1966) attempted a mass spectrometric determination of both uranium and thorium isotopes in geological material. Problems were encountered in these earlier studies in obtaining a sufficient flux of thorium ions. However work in the nuclear industries during the early 1970s using isotope mass spectrometers with rhenium filaments established the optimum temperatures for measuring thorium ions (Heumann 1972), so that by the mid seventies routine analysis of uranium and thorium was being carried out by mass spectrometry in the nuclear industry (Baeckmann *et al* 1973; de Bièvre 1978). Despite this work, mass spectrometric determination of thorium and uranium from corals and speleothem samples is still in its infancy.

A P P E N D I X   2

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UK PLEISTOCENE MAMMALS USED IN THE CLUSTER ANALYSES

Code No	Insectivora (hedgehogs, shrews, moles, tenrecs, desmans)	
1	*Erinaceus europaeus*	European hedgehog
2	*Sorex araneus*	Common shrew
3	*Sorex minutus*	Pigmy shrew
4	*Sorex runtonensis*	Extinct shrew
5	*Sorex savini*	Extinct shrew
6	*Neomys newtoni*	Extinct water shrew
7	*Neomys fodiens*	Water shrew
8	*Crocidura cf suaveolens*	Lesser white-toothed shrew
9	*Beremendia cf fissidens*	Extinct shrew
10	*Talpa europaea*	Mole
11	*Talpa minor*	Extinct mole
12	*Desmana moschata*	Russian desman

Code No	Chiroptera (bats)	
13	*Myotis mystacinus*	Whiskered bat
14	*Myotis nattereri*	Natterer's bat
15	*Myotis bechsteini*	Beckstein's bat
16	*Plecotus austriacus*	Grey Long-eared bat
17	*Barbastella barbastellus*	Barbastelle bat

Code No	Primates (lemurs,monkeys, Apes, man)	
18	*Macaca sp*	Macaque monkey
19	*Homo sp*	Man

Code No	Lagomorpha (rabbits,hares, pikas)	
20	*Oryctolagus cuniculus*	Rabbit
21	*Lepus timidus*	Mountain hare
22	*Lepus capensis*	Brown hare
23	*Ochotona pusilla*	Steppe pika

Code No	Rodentia (squirrels, rats, mice, voles, porcupines)	
24	*Spermophilus sp*	Suslik
25	*Sciurus whitei*	Extinct squirrel
26	*Castor fiber*	European beaver
27	*Trogontherium cuvieri*	Extinct beaver
28	*Trogontherium minus*	Extinct beaver
29	*Cricetus cricetus*	Common hamster
30	*Allocricetus bursae*	Extinct hamster
31	*Dicrostonyx torquatus*	Arctic lemming
32	*Lemmus lemmus*	Norway lemming
33	*Lagurus lagurus*	Steppe lemming
34	*Clethrionomys glareolus*	Bank vole
35	*Pliomys episcopalis*	Extinct vole
36	*Mimomys savini*	Extinct water vole
37	*Mimomys pliocaenicus*	Extinct vole
38	*Mimomys rex*	Extinct vole
39	*Mimomys reidi*	Extinct Vole
40	*Mimomys newtoni*	Extinct vole
41	*Mimomys actenburgensis*	Extinct vole
42	*Mimomys pitymyoides*	Extinct vole
43	*Mimomys blanci*	Extinct vole
44	*Arvicola terrestris*	Water vole
45	*Arvicola cantiana*	Extinct water vole
46	*Pitymys arvaloides*	Extinct pine vole
47	*Pitymys gregaloides*	Extinct pine vole
48	*Microtus arvalis*	Common vole
49	*Microtus agrestis*	Field vole
50	*Microtus oeconomus*	Northern vole
51	*Microtus oeconomus* var *Nivalis*	Snow vole
52	*Microtus gregalis*	Tundra vole
53	*Microtus (allophalomys) sp*	Extinct vole
54	*Apodemus sylvaticus*	Wood mouse

Code No	Carnivora (dogs, bears, raccoons, weasels, genets, mongooses, hyaenas, cats)	
55	*Canis lupus*	Wolf
56	*Canis lupus Mosbachensis*	Extinct wolf
57	*Xenocyon lycaonoides*	Extinct dhole
58	*Alopex lagopus*	Arctic fox
59	*Vulpes vulpes*	Red fox
60	*Ursus arctos*	Brown bear
61	*Ursus deningeri/Spelaeus*	Cave bear
62	*Meles meles*	Badger
63	*Mustela erminea*	Stoat
64	*Mustela nivalis*	Weasel
65	*Mustela putorius*	Polecat
66	*Lutra lutra*	Otter
67	*Aonyx antiqua*	Extinct otter
68	*Aonyx sp*	Extinct otter
69	*Martes martes*	Pine martin

70	*Gulo gulo*	Wolverine
71	*Crocuta crocuta*	Spotted hyaena
72	*Hyaena brevirostris*	Extinct hyaena
73	*Felis sylvestris*	Wild cat
74	*Felis cf lunensis*	Extinct cat
75	*Lynx lynx*	Lynx
76	*Panthera leo*	Lion
77	*Panthera pardus*	Leopard
78	*Panthera gombaszogensis*	Extinct jaguar
79	*Homotherium latidens*	Sabre-toothed cat
80	*Homotherium sainzelli*	Sabre-toothed cat

Code No	Pinnipedia (seals)	
81	*Phoca sp*	Seal
82	*Trichechus huxleyi*	Walrus

Code No	Proboscidea (elephants)	
83	*Palaeoloxodon antiquus*	Straight-tusked elephant
84	*Mammuthus trogontherii*	Extinct elephant
85	*Archidiskodon meridionalis*	Extinct elephant
86	*Mammuthus primigenius*	Mammoth
87	*Anancus arvernensis*	Gomphothere mastodont

Code No	Perissodactyla (horses, asses, zebras, tapirs, rhinoceroses)	
88	*Equus ferus*	Horse
89	*Equus caballus sp*	Caballine horse (extinct)
90	*Equus stenonis*	Extinct horse
91	*Dicerorhinus etruscus*	Extinct rhino
92	*Dicerorhinus kirchbergensis*	Extinct rhino
93	*Dicerorhinus hemitoechus*	Extinct rhino
94	*Coelodonta antiquitatis*	Woolly rhino

Code No	Artiodactyla (pigs, hippopotamuses, camels, deer, giraffes, cattle, sheep, goats, antelopes)	
95	*Sus scrofa*	Wild boar
96	*Hippopotamus major*	Extinct hippo
97	*Hippopotamus amphibius*	Hippo
98	*Cervus elaphus*	Red deer
99	*Capreolus capreolus*	Roe deer
100	*Dama dama*	Fallow deer
101	*Dama dama var Clactoniana*	Extinct fallow deer
102	*Megaceros verticornis*	Giant deer
103	*Megaceros giganteus*	Giant deer
104	*Eucladoceros falconeri*	Extinct deer
105	*Eucladoceros sedgwicki*	Extinct deer

106	*Eucladoceros tetraceros*	Extinct deer
107	*Alces alces*	Elk
108	*Alces latifrons*	Extinct elk
109	*Rangifer tarandus*	Reindeer
110	*Bison schoetensacki*	Extinct bison
111	*Bison priscus*	Extinct bison
112	*Bos primigenius*	Aurochs
113	*Ovibos moschatus*	Musk ox
114	*Gazella angelica*	Extinct gazelle
115	*Saiga tartarica*	Saiga antelope
116	*Ovis/capra sp*	Sheep or Goat
117	*Hemitragus sp*	Extinct sheep
118	*Soergelia elizabethae*	Extinct sheep

Code No	Cetacea (whales, dolphins, porpoises)	
119	*Cetacea sp*	Whale, Dolphin or Porpoise

TABLE A2.1 : UK CAVE MAMMAL FAUNA SITES EXCLUDING THE MENDIP REGION

Location	Code Number of Mammals Present	Source
Dove Hole, Derbyshire	80,85,87,89	Spencer & Melville 1974
Kent's Cavern, Devon:		Campbell & Sampson 1971
B1 Breccia	45,47,59,61,76,79	
A2 Loamy Cave Earth	55,59,60,62,71,76,86,88,94,103,111	
B2 Black Band	59,60,62,71,76,88,94,103,111	
Pontnewydd Cave, Nth Wales:		Currant 1984
Intermediate Complex (Type I)	19,26,45,52,54,55,60,77,88,93,99	
Lower Breccia (Type II)	23,32,44,50,52,55,66,71,77,88,92,93,98,111	
Silt Beds & Upper Breccia (Type III)	21,31,55,59,60,88,109,113	
Tornewton Cave, Devon:		Sutcliffe & Zeuner 1962
Glutton Stratum	29,30,31,32,33,34,44,49,50,51,54,55,59,60,62,67,70,76,88,93,109,111	Sutcliffe & Kowalski 1976
Bear Stratum	31,32,33,34,44,49,50,51,60	
Hyaena Stratum	21,44,49,54,55,59,60,71,76,93,97,98,100,111	
Elk Stratum	55,59,60,71,88,94,98,103,109,111	
Reindeer Stratum	10,19,21,31,34,44,49,50,52,55,59,60,71,88,109,111	
Kirkdale Cave, Yorkshire	22,34,44,49,54,55,59,60,63,71,76,83,93,97,98,100,103,111	Boylan 1981
Victoria Cave, Yorkshire	60,71,76,83,93,97,98,103,111	Gascoyne *et al* 1981
Joint Mitnor, Devon (Beds 3 and 4)	44,49,55,59,60,62,71,73,76,83,93,95,97,98,100,103,111	Sutcliffe 1960
Minchin Hole, Gower:		Sutcliffe 1984
Neritoidies Beach & Earthy Breccia	49,50,54,60,71,76,93,95,98,100	
Ossom's Cave, Peak Dist:		Bramwell *et al* 1983
Bed D	16,31,32,44,49,50,111	
Bed C	2,3,13,19,21,31,32,34,44,49,50,109,111	
Elder Bush Cave, Staffs:		Bramwell 1964
Layer 7	55,59,60,71,76,97,103,109,111	
Layer 9 (Lower)	2,3,31,32,44,48,50,54,55,59,60,61,64,71,76,88,94,103,109,111	
Layer 10	31,32,34,44,48,50,64,109	
Layer 12	44,54,55,59,62,65,73,94,98,111,116	
Inchnadamff Cave, Scotland:		Newton 1917
Bed 5	21,31,49,50,60,63,64	
Bed 3	19,66,75,98,109	
Dog Hole, Peak District	2,3,13,14,16,17,26,34,54,55,59,64,73,88,95,98,112	Jenkinson *et al* 1984
Cales Dale Cave	1,34,44,55,59,62,73,75,88,95,99,112	Jenkinson 1984a
Lynx Cave, Clwyd (Layer C)	44,59,75,99,112	Jenkinson 1984a
Kinsey Cave	55 60,75,109,112	Jackson 1932
Teesdale Fissure	55,59,62,75,95,98,109,112	Jenkinson 1984a
Lynx Cave, Staffs	55,59,65,75,112	Jackson 1962
Yew Tree Cave	55,59,75,95,99	Jenkinson 1984b
Robin Hood Cave	55,59,60,62,73,75,88,98,99,107,112	Campbell 1969,1977
Steetley Cave	1,2,10,34,62,73,75,95,98,99,112	Jenkinson 1984a

Table A2.1 (continued

Location	Code Number of Mammals Present	Source
Bacon Hole Cave;		
Sandy Cave Earth	2,3,21,32,45,49,54,59,76,83,98,100,112	Stringer 1975,1977
Grey Clays	2,32,45,49,50,54,62,71,86,93,100,111,112	Stringer *et al* 1986
Upper Cave Earth	45,50,55,71,83,93,98,112	

TABLE A2.2 : UK 'OPEN' MAMMAL FAUNA SITES

Location	Code Number of Mammals Present	Source
Red Crag (Suffolk)	21,26,55,59,82,85,87,89,90,102,104,105,106,114,119	Spencer 1964,1966,Stuart 1982
Blake's Pit (Lower Shell Bed)	37,38,39,40,41,68,81,85,105	Funnell *et al* 1979, Mayhew 1985
Thorpe/Norwich	27,37,39,40,41,90,104,114	Stuart 1982, Mayhew 1985
Easton Bavents	37,39,43,85,87,96,102,104,105,119	Spencer 1964, Carreck 1967
West Runton (Crag)	37,39,40,42,43,85	Stuart 1982, Mayhew 1985
East Runton (Crag)	37,39,40,42,43	Mayhew 1985
W Runton (Cromer Forest Beds):		Stuart 1975
A	4,5,10,12,34,48,50	
B	5,6,10,12,34,48,54	
C	4,5,34,48,54,64	
Sugworth	3,5,9,11,34,35,36,48,54,98,110	Stuart 1980
Ostend	4,5,10,12,25,27,34,45,48,84,89,99	Stuart & West 1976
Clacton	19,27,34,45,48,76,83,88,92,93,95,98,100,112	Stuart 1982
Swanscombe (Lower Gravel + Loam)	11,18,19,20,26,45,46,48,50,55,61,69,73,76,83,88,92, 93,95,98,99,100,103,112	Sutcliffe 1964, Stuart 1982
Swanscombe (Upper Middle Gravel)	19,21,32,48,50,55,76,83,88,93,98,100,103,112	Sutcliffe 1964, Stuart 1982
Ingress Vale	19,27,34,45,54,76,83,88,92,93,95,98,100,112	Stuart 1982
Hoxne	2,12,18,19,26,27,32,45,49,83,88,98,99,100,102,111	Gladfelter & Singer 1975
Selsey	19,26,83,88,93	West & Sparks 1960
Bobbitshole	26,34,45,49,54	
Sewerby-Hessle Buried Cliff	44,60,71,83,88,93,111	Boylan 1967
Swanton Morley	2,3,34,45,49,50,54,71,97,98,100,112	Coxon *et al* 1980
Barrington	45,49,55,60,62,71,76,83,93,97,98,100,103,111,112	Gibbard & Stuart 1975
Trafalgar Square	76,83,93,97,98,100,103,111,112	Stuart 1982
Aveley	8,34,45,49,83,86,88,98,111	Stuart 1976
Stutton	2,7,19,26,34,45,49,50,54,76,83,86,88,98,103,111	Stuart 1976
Harkstead	34,83,86,88,98,111	
Ilford	26,45,60,76,83,86,88,93,98,103,111,112	West *et al* 1964
Stoke Tunnel	19,45,49,50,55,60,76,86,88,94,98,111	Stuart 1976
Crayford	19,24,31,32,50,55,60,76,86,88,93,94,98,103,111,112,113	Kennard 1944
Marsworth (Upper Channel)	44,93,97,98,103,111	Green *et al* 1984
(Lower Channel)	50,55,60,76,86,88,89,111	
Thatcham	1,2,10,19,20,26,44,55,59,62,69,73,88,95,98,99,107,112	Stuart 1982
Star Carr	1,19,26,55,59,62,69,73,95,98,99,107,112	Stuart 1982
Wallingford	32,45,52,88,109	Stuart 1982
Homersfield	86,88,94,103,109,111	Stuart 1982
Baginton-Lillington Gravels	71,86,88,94,109,111	Shotton 1968
Wretton	55,58,60,86,88,94,109,111	West *et al* 1974
Coston	45,49,86,94,98,109,111	Stuart 1982
Isleworth	50,52,55,60,86,88,94,103,109,111	Stuart 1982
Tattershall Castle	52,55,60,86,88,94,109,111	Stuart 1982
Upton Warren	31,86,88,94,109,111	Coope *et al* 1961
Kirkby-on-Basin	86,88,94,98,103,111	Stuart 1982
Beckford	52,86,88,94,111,113	Stuart 1982

TABLE A2.3 : MENDIP REGION MAMMAL FAUNA

Location	Code Numbers of Mammals Present	Source
Westbury-sub-Mendip:		Bishop 1982
Bed 1	26,36,53,72,74,91,101,110	
Bed 3	17,56,57,61,63,70,71,74,78,79,89,98,111,116	
Bed 4	16,17,21,56,57,61,76,78,79,89,98,101,111	
Bed 5	4,5,10,16,17,21,32,34,45,47,48,54,56,57,59,61,71,76,78,79,89,91, 98,111,117,118	
Bed 6	56,61,76,78,98,111	
Bed 8	46,47,48,61,78,111	
Bed 10	1,3,4,5,6,10,11,12,16,31,32,34,35,45,46,47,48,50,54,56,61,63,64, 101,111	
Milton Hill (Wells)	71,83,97,98,99,103,109,111,112	Balch 1937
Durdham Down (Bristol)	55,59,60,61,62,66,71,76,83,86,88,93,97,109	Dawkins 1869, Balch 1937
Cleavdon (Walton) Cave	20,49,50,51,52,55,58,59,60,88	Reynolds 1906
		Sutcliffe & Kowalski 1976
Picken's Hole - Layer 3	19,24,50,58,60,71,76,86,88,94,98,109,111	Stuart 1982
- Layer 5	50,52,55,59,60,98,109,111	
Soldier's Hole:		Parry 1931
Layer 3 (Spit 4-9)	21,23,31,44,48,52,60,109,111	
Layer 4 (Spit 10-17)	7,21,31,44,52,55,59,60,71,76,86,88,98,103,109,111	
Chelm's Coombe (Spit 1-5)	3,19,67,88,95,98,112,116	Balch & Palmer 1927
(Spit 6-22)	10,19,21,23,31,44,48,49,50,52,54,58,59,63,70,88,95,98,109	
Aveline's Hole (0-30cm)	2,15,21,23,31,32,34,44,48,55,59,60,62,65,88,95,98,109,111	Davis 1925
(30-60cm)	13,21,31,32,34,44,49,50,52,54,59,60,62,75,88,98,109	
(60-90cm)	15,21,32,34,44,48,49,52,59,60,62,98,112	
Banwell Bone Cave	21,32,44,51,52,55,59,60,76,88,95,98,103,109,111,112	Turner 1981, Balch 1937
Hutton Cavern	30,31,32,34,50,55,59,60,71,76,77,86,88,95,103,109,111,112	Balch 1937
		Sutcliffe & Kowalski 1976
Bleadon Cavern	24,31,32,48,49,50,52,55,59,60,71,76,77,83,86,88,95,98,103,109,111	Balch 1937, Reynolds 1906
Freshford (Bath Gravels 23-30m)	86,94,95,109,111,113	Boreland 1985
Larkhall " "	60,83,86,88,94,95,109,112	Boreland 1985
Loxbrook " "	76,86,94,103,109,112	Boreland 1985
Morefield " 46mOD	86,94,98,109,112	Boreland 1985
Victoria Pit " "	83,86,88,94,112	
Sun Hole (Unit 1)	10,19,21,23,26,31,32,34,44,48,50,52,54,55,59,60,64,73,88,109,115	Colcutt *et al* 1981
Gough's Cave - Spit 6-24	19,21,26,32,44,55,58,59,60,88,98,109,112,115	Currant 1984
Spit 7	19,21,59,109,112	
Spit 8	21,55,59,88,109	
Spit 9	19,21,55,60,88,112	
Spit 10	19,21,26,59,88,109,112	
Spit 11	19,21,23,32,44,58,59,60,88,98,109,112	
Spit 12	19,21,44,59,60,88,98,112	
Spit 13	19,21,44,55,60,88,98	
Spit 14	19,21,26,55,58,60,88,98,109,115	
Spit 15	19,21,55,59,88,98,112,115	
Spit 17	21,55,59,88,98	
Uphill 7 and 8	32,52,59,60,62,71,76,86,88,94,98,103,111	Harrison 1977
Uphill 3	19,54,55,59,62,73,95,100,112	Harrison 1977
Sandford Hill	55,60,71,76,88,94,109,111	Turner 1981
Hyaena Den (Wookey Hole)	19,55,59,61,71,76,86,88,94,98,103,109,111	Tratman *et al* 1971
Badger Hole (Wookey Hole)	19,31,52,59,60,66,71,73,86,88,94,103,109,111	Campbell 1977
Brean Down (Bed 11-13)	21,31,49,52,55,58,86,88,103,109,112	Apsimon *et al* 1961
Goatchurch Cavern	60,61,62,73,86,95,111	Balch 1937
Banwell Ochre Mines	21,23,44,50	Hunt 1956
Bridged Pot (Ebbor Gorge)	21,23,31,32,44,48,49,50,52,55,58,59,60,61,64,88,99,103,109	Balch 1937
Rowberrow Cavern:		Taylor 1926
Cemented Floor	2,23,31,54,55,88,98,109	
Layers 2,3 & 4	2,21,34,54,55,59,62,64,65,73,88,95,98,99,116	
Gorsey Bigbury	55,95,98,99,112,116	Apsimon *et al* 1976
Charterhouse Warren Farm	20,21,55,88,95,98,99,112,116	Everton 1975, Burleigh & Clutton-Brock 1977
Hay Wood Cave	20,26,34,44,48,49,50,54,55,59,62,73,88,95,99,112	Everton 1972
Tom Tivey's Hole (Layer 1-3)	2,20,34,44,49,50,54,55,59,64,73,88,95,98,112	Barrett 1966

A P P E N D I X 3

CLUSTER ANALYSIS

Cluster analysis is a generic term that encompasses a large range of statistical classification procedures which, since the advent of high speed computers during the 1960s, have rapidly expanded in number. Well over 100 different clustering algorithms have been proposed, yet no adequate statistical theory exists that would allow the different advantages of these algorithms to be distinguished (Blashfield & Aldenderfer 1978, Blashfield 1980). Jardine and Sibson (1968) and Hubert (1972,1974) demonstrated that the 'single linkage' and 'complete linkage' methods of Johnson (1967) would theoretically yield the most perfect cluster solutions. This work resulted in many researchers using these hierarchical methods, although the results were often poor. These problems and the end of the 'Quantitative Revolution' in geography during the late 1970s (Slater 1977) led to a general disenchantment with multivariate statistical techniques such as cluster analysis, so relatively little modern 'geographical' literature exists concerning choosing between different clustering algorithms for analysing 'geographical' data sets. Fortunately a number of empirical evaluation studies by psychologists during the late 1970s and the 1980s have led to a series of recommendations on which methods have the greatest utility.

The results of Monte Carlo studies with continuous data have shown

(1) hierarchical algorithms generally produce more reliable cluster solutions than non-hierarchical methods;

(2) single linkage and complete linkage algorithms generally fail to resolve cluster structure with real data sets due to their high sensitivity to chaining (cluster overlap). They are however very efficient at clustering ideal or perfect data sets;

(3) the efficiency of cluster recovery is dependent both on the nature of the data set, as would be expected, but also on the distance measure used to construct the similarity matrix;

(4) Ward's method is the most robust method using a similarity matrix constructed from Euclidean distances. It is particularly good at recovering cluster structure even when considerable cluster overlap is present;

(5) average linkage is the optimal method with correlation coefficient similarity matrices. It is particularly robust to the presence of outliers in the data set.

(Bayne *et al* 1980; Blashfield 1976,1977; Blashfield & Morey 1980; Edelbrock 1979; Edelbrock & McLaughlin 1980; Milligan 1980,1981; Morey *et al* 1983; Scheibler & Schneider 1985.)

If the data set to be analysed has not been subjected to multivariate tests for outliers or there is no *a priori* reason to assume that outliers are not present, then it would seem wise to cluster using both Ward's method (with Euclidean Distance) and Average Linkage (using correlation). It must be noted that Ward's method is such a robust algorithm that it will even produce a cluster solution with multivariate normally distributed data (ie no true clusters) if there is sufficient variation along the first principal component axis (Morey *et al* 1983). This is not necessarily a problem since a partitioning on this basis is often as useful for classification purposes as true clusters (Morey *et al* 1983).

Clustering Binary Data

In comparison with continuous data, studies of categorical data clustering algorithms are in their infancy. The number of binary similarity matrix coefficients is also markedly smaller. The 17 most commonly used are (Wishart 1979):

If
A = No. of attributes in common to both cases I and J,
B = No. of attributes present in case I, absent in case J,
C = No. of attributes absent in case I, present in case J,
D = No. of attributes absent in both I and J,
M = Total No. of attributes,
M = A + B + C + D,

Then

(1) Euclidean Distance $= \frac{B + C}{M}$

(2) Error sum of squares $= \frac{B + C}{2M}$

(3) Information gain statistic $= 2\,(B + C) \log 2$

(4) Variance $= \frac{B + C}{4M}$

(5) Size difference $= (B - C)^2/M^2$

(6) Shape difference $= M\,(B + C) - (B - C)^2/M^2$

(7) Simple matching $= \frac{A + D}{M}$

(8) Hannan $= \frac{(A + D) - (B + C)}{M}$

(9) Sokal & Sneath $= \frac{2\,(A + D)}{2\,(A + D) + (B + C)}$

(10) Rogers & Tanimoto $= \frac{A + D}{A + D + 2\,(B + C)}$

(11) Jaccard $= \frac{A}{A + B + C}$

(12) Correlation $= \frac{AD - BC}{\sqrt{(A + B)\,(A + C)\,(B + D)\,(C + D)}}$

(13) Kucizywski $= \frac{A}{B + C}$

(14) Sokal & Sneath 2 $= \frac{A + D}{B + D}$

(15) Yule $= \frac{AD - BC}{AD + BC}$

(16) Dot product $= \frac{A}{M}$

(17) Cosine $= \frac{A}{\sqrt{(A + B)\,(A + C)}}$

There is virtually no theoretical or empirical work that has compared the performance of these different similarity coefficients or the partition methods that can be used to cluster from them. Most researchers have used the simple matching coefficient for similarity matrix construction when clustering, although there is no 'scientific' reason for using this in preference to the other methods (Everitt 1980), particularly since it is often used in conjunction with 'Ward's' method which is designed to work on 'distance' measures rather than 'similarity' measures (Ward 1963). However, this may not be a significant problem in practice since with dichotomy variables Euclidean distance = 1-simple matching coefficient. Therefore, the resulting clusters will be identical in most cases.

Hands & Everitt (1987) have demonstrated that the performance of hierarchical clustering techniques when applied to categorical data is influenced by the

(1) number of groups,
(2) number of variables,
(3) sample size,
(4) mixing proportions (cluster overlap).

They compared the performance of different clustering algorithms by Monte Carlo studies with simple matching coefficient similarity matrixes and found that

(1) single linkage yielded worse results than other techniques;

(2) clustering accuracy increased markedly with increasing numbers of variables and decreasing numbers of groups (clusters);

(3) Ward's method outperforms other methods under most circumstances;

(4) if the proportion of observations in each group is very different, the centeroid method is superior to Ward's method.

Cluster Validation

A major problem with many 'geographical' cluster analysis studies is that only the dendrogram of the cluster solution is presented. No systematic attempt is often made to show which variables are common in a cluster and/or which variables distinguish one cluster from another. The statistical validity and nature of the cluster solution is also seldom discussed. This situation is unsatisfactory as the reader has no way of assessing the likely validity of the cluster solution. It can be considered analogous to a univariate study where the means of the data sets are presented without either the raw data or the standard deviations of the means.

There are three main factors which should be considered when assessing the validity of a cluster solution. These are:

1) the amount of distortion between the hierarchical solution and the similarity/dissimilarity matrix;

2) the statistical validity of any given level of the hierarchical cluster solution;

3) the optimum level of the hierarchical cluster solution (eg the optimum number of clusters).

Many clustering algorithms will impose a hierarchical structure upon a given data set even where no such structure exists. Therefore it is necessary to measure the amount of 'distortion/correspondence' between the hierarchical solution and the original proximity matrix (eg the data). The most frequently used measure is the Cophenetic Correlation Coefficient which is the product moment correlation between the $n(n-1)/2$ entries in the proximity matrix and the $n(n-1)/2$ entries in the Cophenetic matrix (solution matrix). The value of this statistic ranges between -1 and +1 with a value of +1 indicating a perfect match (Sokal & Rohlf 1962). Although the Cophenetic Correlation Coefficient is widely used, Holgerson (1978) has shown that it can be a misleading indicator. Jardine & Sibson (1971) have proposed several alternative distortion measures. These are:

$$\Delta_0 = \max (A_{ij} - B_{ij}) / \max B_{ij}$$

$$\Delta_1 = \Sigma ((A_{ij} - B_{ij})^2 / \Sigma B_{ij})^{1/2}$$

$$\Delta_2 = \Sigma A_{ij} - Bij / \Sigma B^{ij}$$

These three delta statistics all have the value of 0 when there is a perfect match and no maximum value. However it must be stressed that the utility of these statistics is unknown.

The problems of assessing the statistical significance of clusters at any given level (number of clusters) of the complete solution has been addressed by Mojena (1977) who has defined a significant solution as one where (Rule 1):

$$Zj + 1 > Z + KS_z$$

where Zj = the value of the clustering criteria at the j fusion (eg the dendrogram y axis value)

Z = the mean of all the fusion criteria values

S_z = the standard deviation

K = the standard deviate

The t statistic can be used to assess the significance of any clustering level as:

$$t = \sqrt{n - 1} * \text{the realised deviates}$$

However the use of the t statistic assumes normality which is unlikely. Another problem with this procedure is that it is biased by the inclusion of the Zj cluster criterion being tested in the calculation of the mean. To overcome this problem Mojena (1977) has proposed a moving rule (Rule 2) where significance is defined as:

$$Zj + 1 > Zj + Lj + bj + Sj$$

where Zj = the moving mean at stage j

Lj = the correction trend lag at stage j

bj = the moving least squares slope at stage j

Sj = the moving unbiased estimate of the population standard deviation at stage j

Identifying the optimum number of clusters in any given solution is one of the "major unsolved problems of cluster analysis" (Everitt 1979). The problem results from the lack of theoretical studies of cluster analysis as there is no agreed definition of what 'optimum solution' means (Aldenderter & Blashfield 1984). Mojena (1977) has argued that a large jump in the value of the Realised Deviates under Rule 1 (see above) can be used to identify an optimum solution. However this seldom yields definitions that differ from visual inspection of a cluster dendrogram (Dunn & Everitt 1982).

APPENDIX 4

The Cilas 715 laser granulometer currently represents the 'state of the art' technology that is commercially available to industry for particle size analysis (*per com* from unpublished Scotland Yard forensic laboratory assessment of particle size analysis techniques *circa. 1985). They work on the principle that coherent light when directed through a suspension of powder sample will be defracted according to the Airy equation:*

$$r = \frac{1.22\ \lambda\ F}{D}$$

where r = the radius of the first bright defraction ring

λ = the wave length of the light source

D = the objective lens diameter

F = the objective lens focal length.

The masses of the particle of different sizes can be calculated by measuring the intensity of the defraction at set positions. The Cilas 715 laser granulometer uses 16 photo detectors to measure particles with maximum diameters of 1, 1.5, 2, 3, 4, 6, 8, 12, 16, 24, 32, 48, 64, 96, 128 and 196 um.

The light intensity is measured 128 times for each photocell and the results integrated to ensure stability (J. Wong per com). Other laser defraction machines are now commercially available which will measure different particle sizes (H. Rendal *per com*). However discussion will be confined to the Cilas 715 which is the most widely available model.

Although several researchers are beginning to use laser granulometers (eg Oxford and Sussex University Geography Departments have purchased machines), no evaluation of them has appeared in the geographical literature. Figure A.4.1 shows the particle size result from certified quartz reference powders BCR 69 and 70 produced using the Cilas 715. These European standard reference powders are obtainable from the Commission of European Communities, Community Bureau of Reference, and were kindly supplied by Rolls Royce Limited. their sizes are measured by sedimentation analysis at the five European Standard Reference Laboratories, and the Cilas 715 results are indistinguishable from the reference laboratory results at plus or minus one standard deviation. Therefore the accuracy of the Cilas 715 is equivalent to that of the European Reference Laboratories.

There are only three variables that influence the precision and accuracy of particle size determination using the Cilas 715. These are:

1) The length of time that samples are dispersed by ultrasonic vibration prior to analysis.

2) The amount of sample used.

3) The speed of analysis, eg do significant numbers of larger particles sediment out as time progresses or are they satisfactorily maintained in suspension by the circulating pump?

Figure A4.2 shows the size of variation of these three variables on the median particle diameter of typical Mendip cave sediments (the median particle diameter always varies to a greater extent than the individual value of any of the sixteen size classes). The total variation in median particle diameter is less than ten per cent even

FIG A4.1A : PARTICLE SIZE ANALYSIS OF BCR 69 USING A CILAS 715
(* represents ± 1σ certified uncertainties of BCR70)

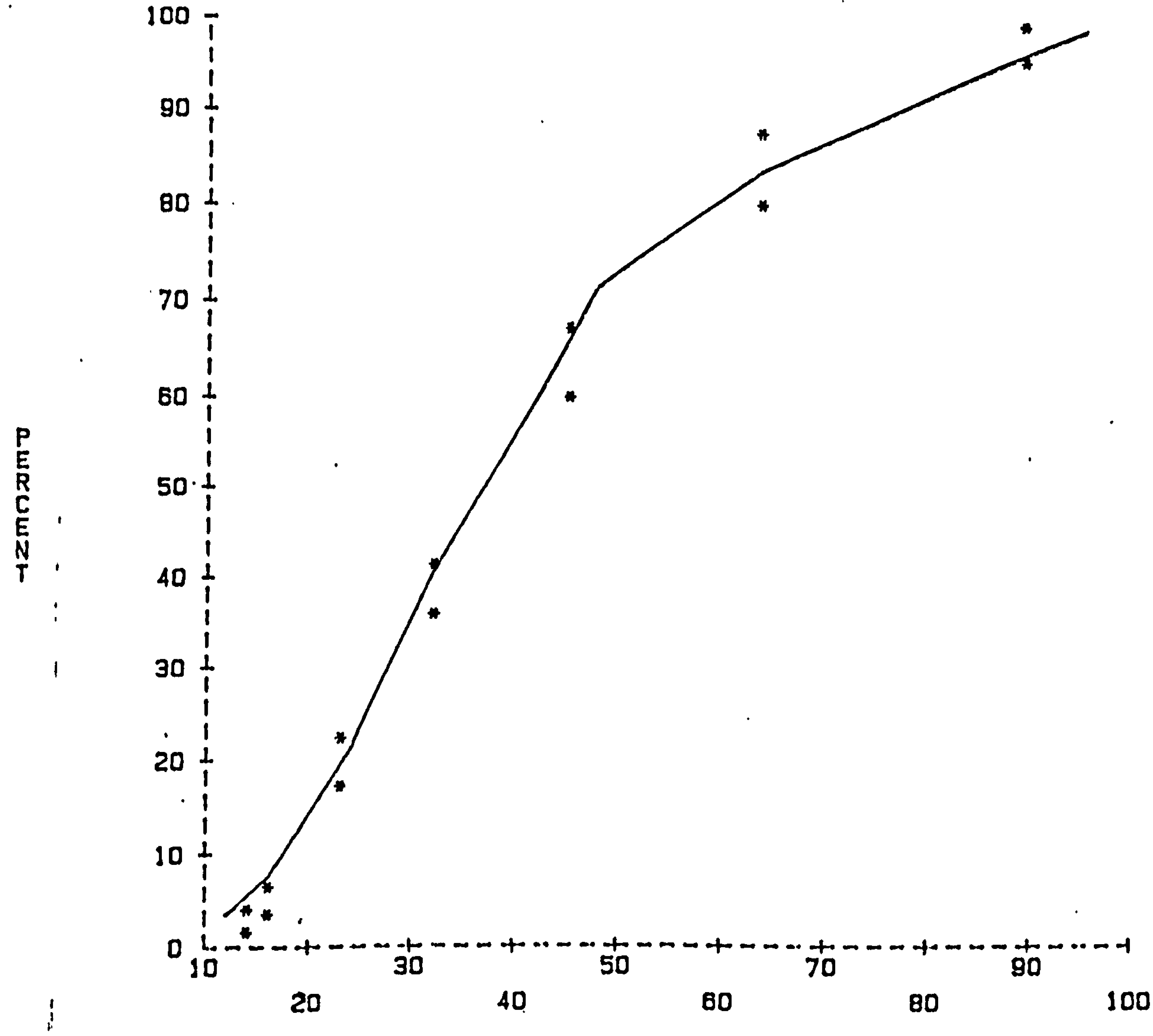


FIG A4.1B: PARTICLE SIZE ANALYSIS RESULTS OF BCR 70 USING A CILAS 715.
(* represents ± 1σ certified uncertainties of BCR70)

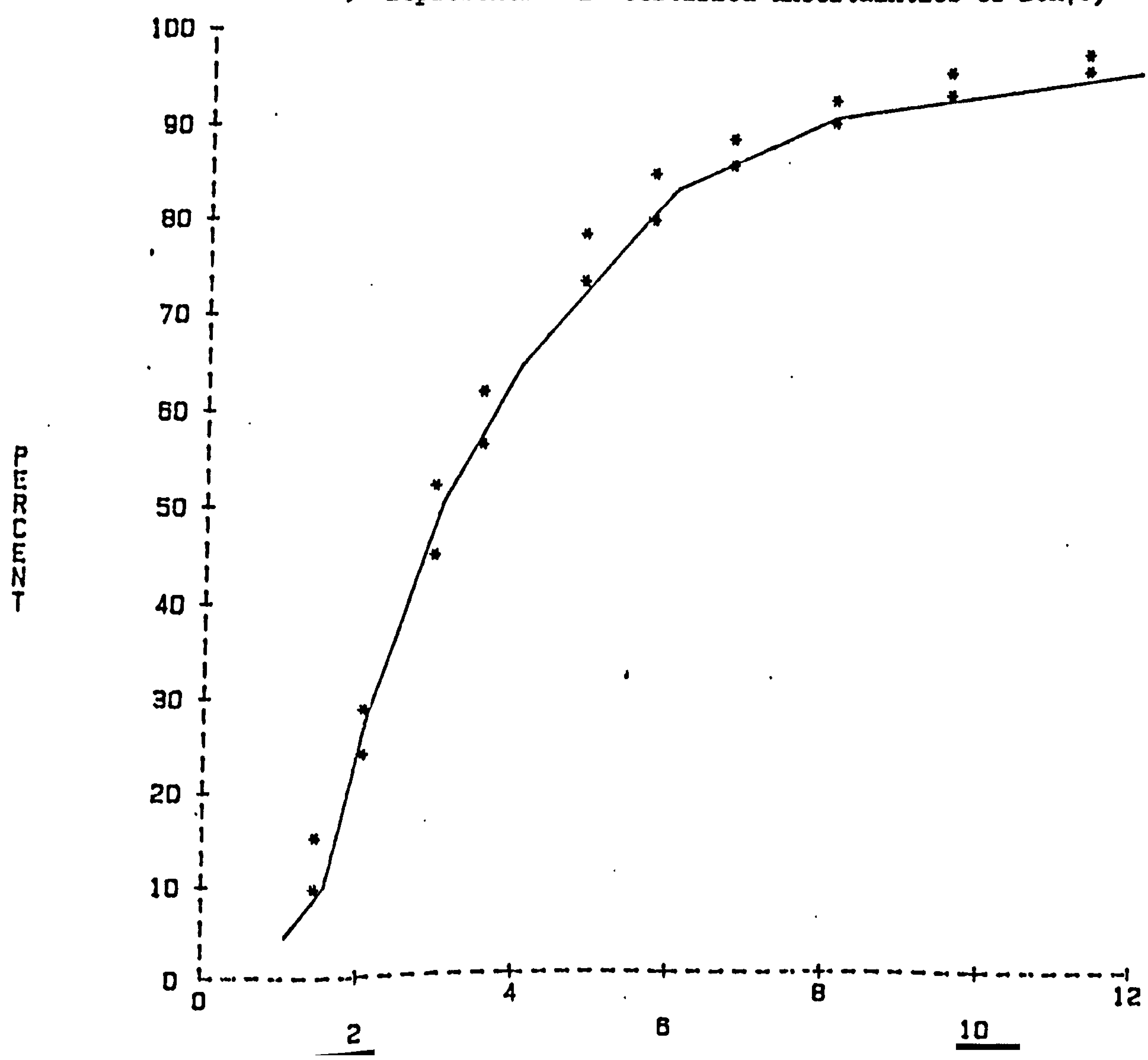
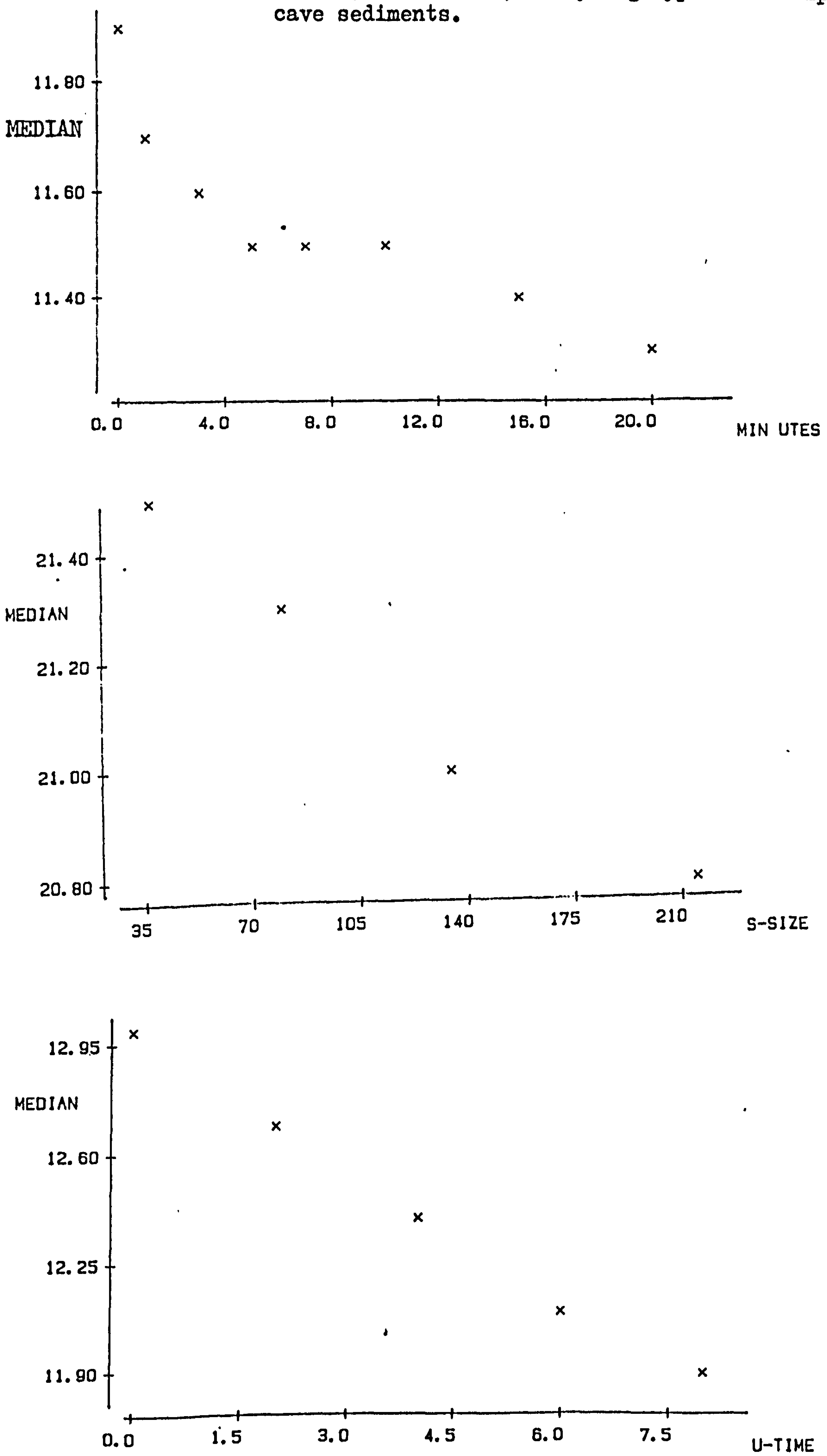


FIGURE A4.2 : Effects of variations in the speed, sample size and amount of ultrasonic dispersion on the median grain diameter results from a Cilas 715 laser granulometer, analysing typical Mendip cave sediments.



when extreme cases are considered. If a standard procedure is adopted with a standard sample size, ultrasonic dispersion for two minutes (see Edwards & Bremner 1967) followed immediately by analysis, then precisions of better than 1% can be achieved using typical Mendip cave sediments. The main cause of variation results from the sub sampling method used (see Chapter VIII). Table A4.1 shows the sub sample particle size variation using a suspension sample splitter similar to that Burt *et al* (1973) compared to the sub sample variation using a syringe and a magnetically stirred suspension. The suspension splitter yields more precise results in all 16 size classes and complete sample precision of 1 to 3% are routinely attainable by this method. However the variation of the fine sand fraction (64-192 um) may be greater than this irrespective of the sub sampling method used. This probably results from the small sample size (approximately 0.2 - 0.5 grammes) required by the Cilas 715 being too small to reliably represent particles in these size ranges (see Chapter VIII).

TABLE A4.1 : Comparison of the precisions of particle size analysis results using a suspension sample splitter similar to that of Burt *et al* (1973), and sampling from a magnetically stirred suspension using a syringe.

Method = Suspension Sample Splitter				Magnetic Stirrer + Syringe		
Sample = WSM W1 S7	n = 5			WSM W1 S1	n = 5	
Particle Size Class (in mm)	Mean (in %)	Standard Deviation	Range (in %)	Mean (in %)	Standard Deviation	Range (in %)
1	3,33	0,05	3,3-3,4	2,0	0,1	1,9-2,1
1,5	1,43	0,05	1,4-1,5	0,84	0,05	0,8-0,9
2	4,35	0,23	4,2-4,7	3,06	0,18	2,9-3,3
3	4,20	0,17	4,1-4,4	4,62	0,32	4,4-5,1
4	3,38	0,05	3,3-3,4	4,8	0,28	4,6-5,2
6	4,7	0,18	4,5-4,9	7,24	0,55	6,8-8,1
8	4,75	0,10	4,6-4,8	6,46	0,38	6,1-7,1
12	6,50	0, 24	6,2-6,7	8,22	0,59	7,6-9,2
16	6,75	0,33	6,5-6,9	8,56	0,31	8,3-8,9
24	8,76	0,19	8,5-9,0	8,96	0,71	8,2-10,1
32	7,8	0,14	7,6-7,9	9,1	0,50	8,6-9,9
48	11,16	0,23	10,8-11,4	14,96	0,32	14,7-15,4
64	6,98	0,42	6,5-7,4	7,3	1,04	5,6-8,1
96	12,42	0,43	11,9-12,7	11,92	2,31	8,2-14,1
128	6,3	0,50	5,5-6,7	0,64	0,23	0,3-0,9
192	4,0	0,21	3,7-4,2	0,52	0,45	0-1,2
Median Grain Diameter = 25,05 (in mm)		0,74	24,4-26,2	19,5	2,38	16-21,7

APPENDIX 5

QUANTIFICATION OF TWO-DIMENSIONAL SHAPES BY RADIAL FOURIER ANALYSIS

There are a number of possible ways that two-dimension shapes can be quantified, for example fractal analysis (Orford & Whalley 1983), asphericity spectrum (Davis & Dexter 1972) and slope density (Mahin 1974). However, the most widely used method is the radial fourier technique of Ehrlich & Weinberg (1970) which has yielded satisfactory results not only in geological/geomorphological studies of clasts (Czarnecka & Gillot 1980) and sand grains (Mazzulo & Ehrlich 1980, Dowdeswell 1982) but also biological studies of complex zooecial shapes (Ansley & Delmet 1973) and in industrial studies of cement (Czarnecka & Gillott 1977a,b). This technique has therefore been well tested and shown to have wide applicability. Ehrlich & Weinberg (1970) argued that clast outlines could be considered as a complex waveform wrapped round upon itself. Therefore if the outline can be converted into a linear wave form (by finding the particle centre) it could be adequately represented by fourier series harmonics. They argued that the first twenty harmonics (Figure A5.1) could adequately characterise most clast shapes, although if greater precisions were required further harmonics could be calculated (up to n-1 where n = the number of points digitized on the outline).

It is clear from Figure A5.1 that overall shape differences will be characterised by the lower order harmonics whereas textural differences will be characterised by variation in the higher order harmonics.

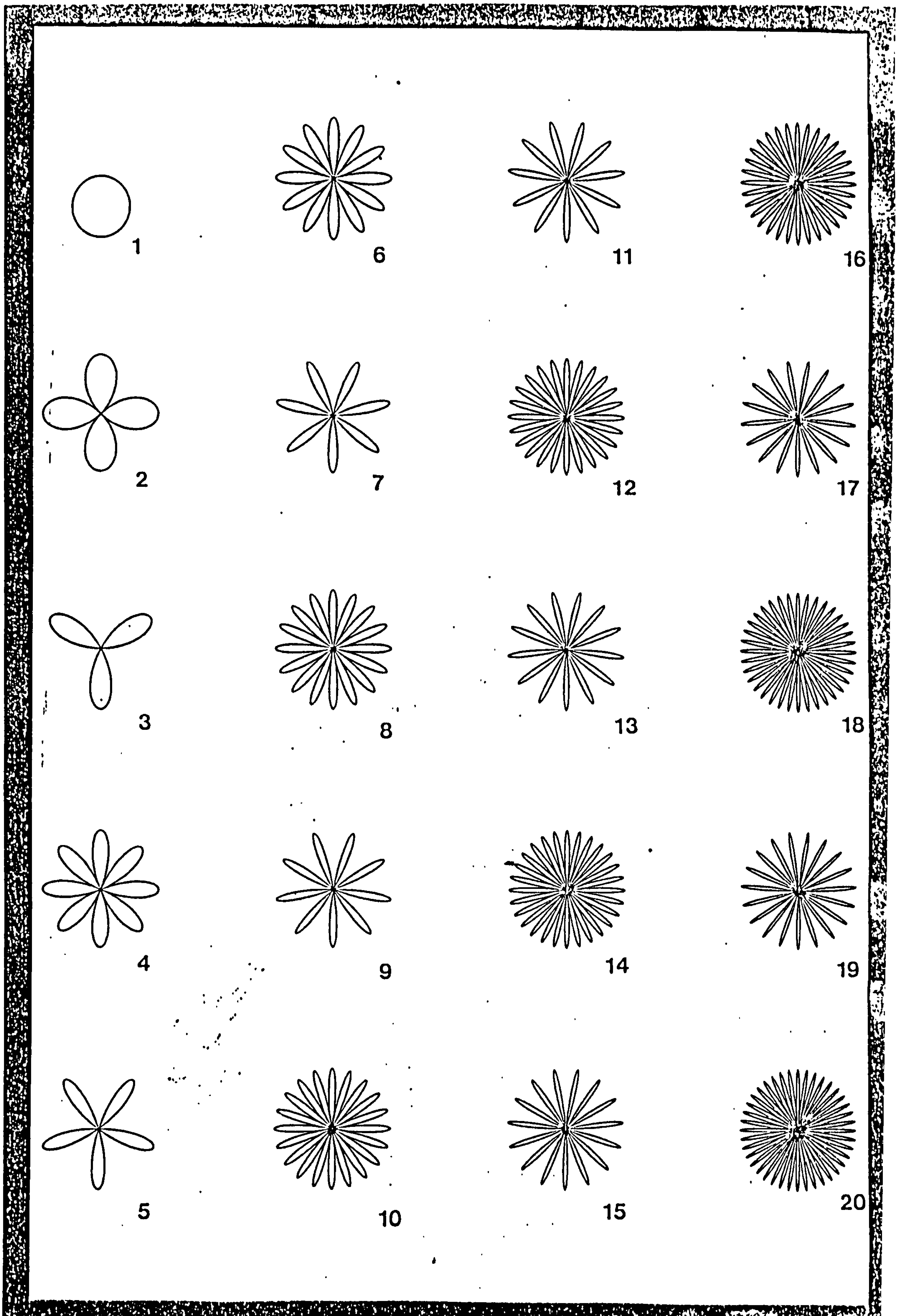
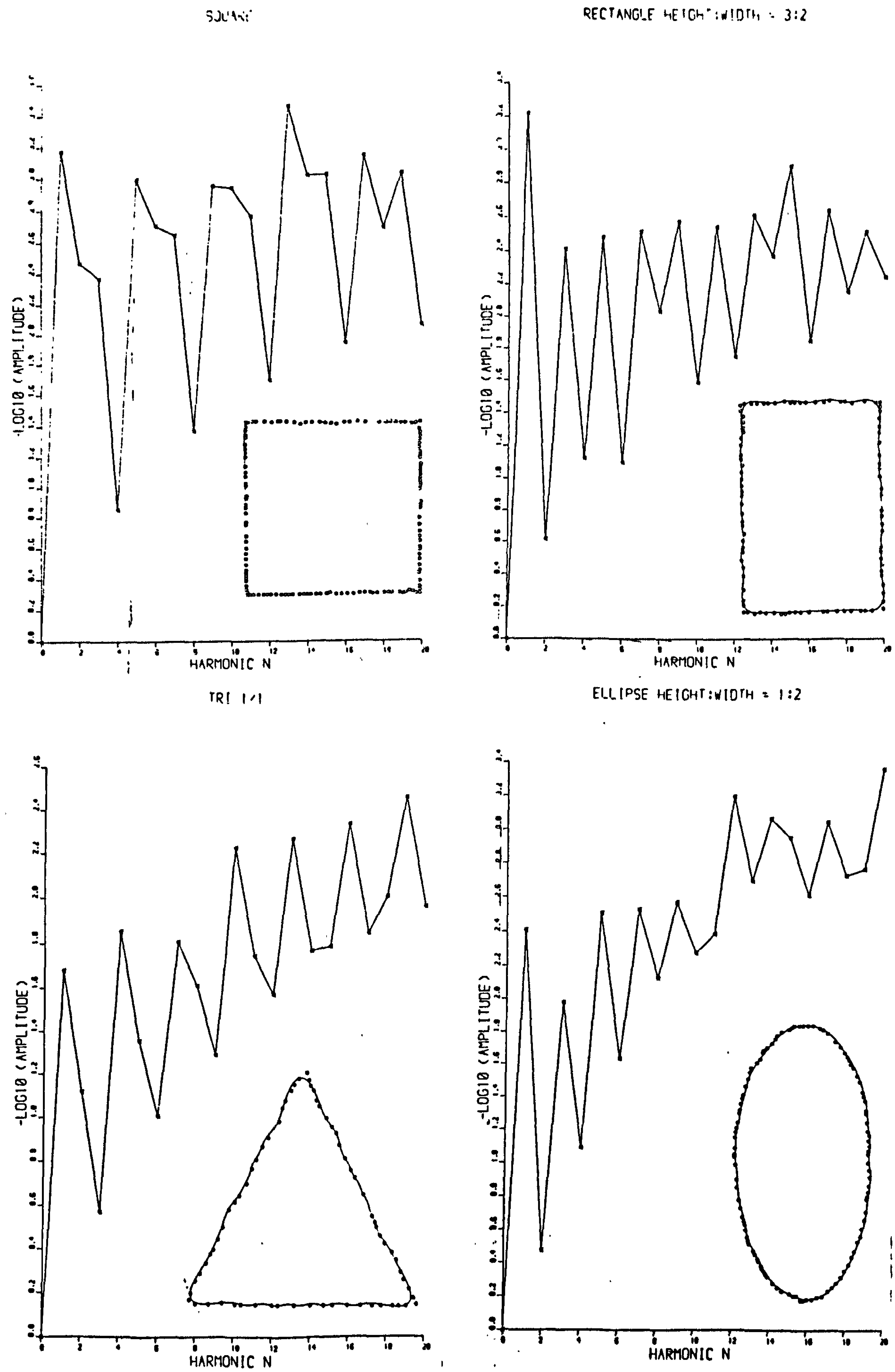


FIGURE A5.1 : Sizes of the first 20 harmonics of a radial Fourier analysis (Ehrlich & Weinberg 1970).

Although the values of the fourier series harmonics are independent of the size of the digitized outline, overall particle size can influence the shape of both sand and gravel sized particles (Bardecki 1977, Erhlich *et al* 1980). It is advisable to standardise shape determinations by confining them to a single size fraction (16-32 mm in this work) and by always resting a particle on its most stable axis before recording its outline (which can be achieved by tracing from a Grant projector.

A number of summary statistics have been proposed that combine the fourier series harmonics in various combinations in order to try to differentiate between smooth and textured particles (Erhlich & Weinberg 1970, Czarnecka & Gillott 1977a). These statistics work well when comparing similar shapes but can give misleading results if overall shape varies. Figure A5.2 illustrates the effect of shape on the fourier series harmonics. It is the pattern of the harmonics rather than their absolute value that is most affected by overall shape differences (eg with triangles every third harmonic has a high value whereas with rectangles every second harmonic has a high value). Therefore it is clear that multivariate analysis will yield superior results to summary statistics in particle populations where there is considerable variation in overall form.

FIGURE A5.2 : Effect of shape on radial Fourier harmonics.



A P P E N D I X 6

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Figure

A6.1 Radial Fourier analysis of limestone clasts from Sample 5, Section W1, Westbury-sub-Mendip.

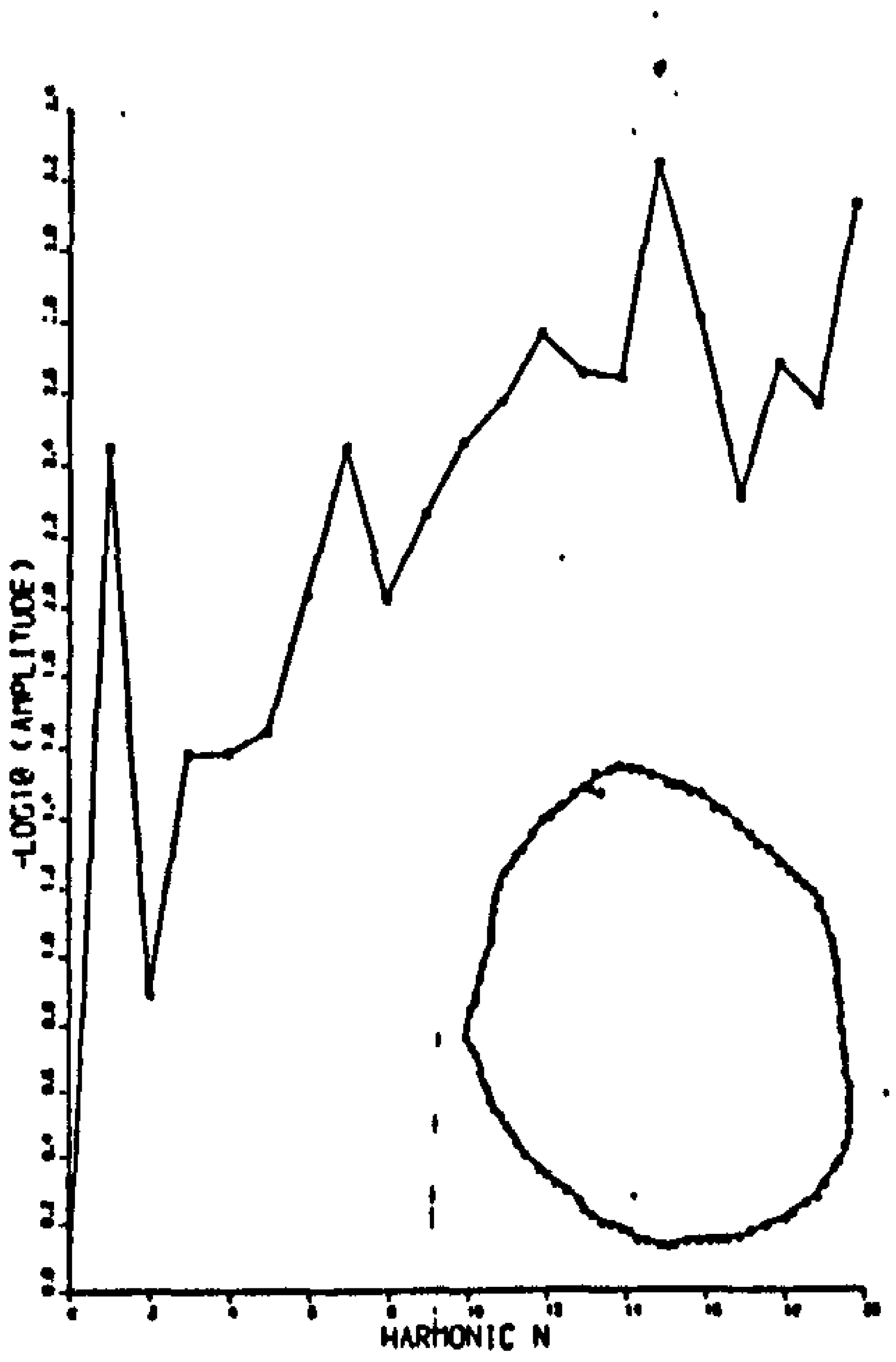
A6.2 Radial Fourier analysis of limestone clasts from Sample 7, Section W1, Westbury-sub-Mendip.

A6.3 Radial Fourier analysis of limestone clasts from Sample 8, Section W1, Westbury-sub-Mendip.

A6.4 Radial Fourier analysis of limestone clasts from Sample 9, Section W1, Westbury-sub-Mendip.

A6.5 Radial Fourier analysis of limestone clasts from Sample 12, Section W1, Westbury-sub-Mendip.

VISS ROCK 1



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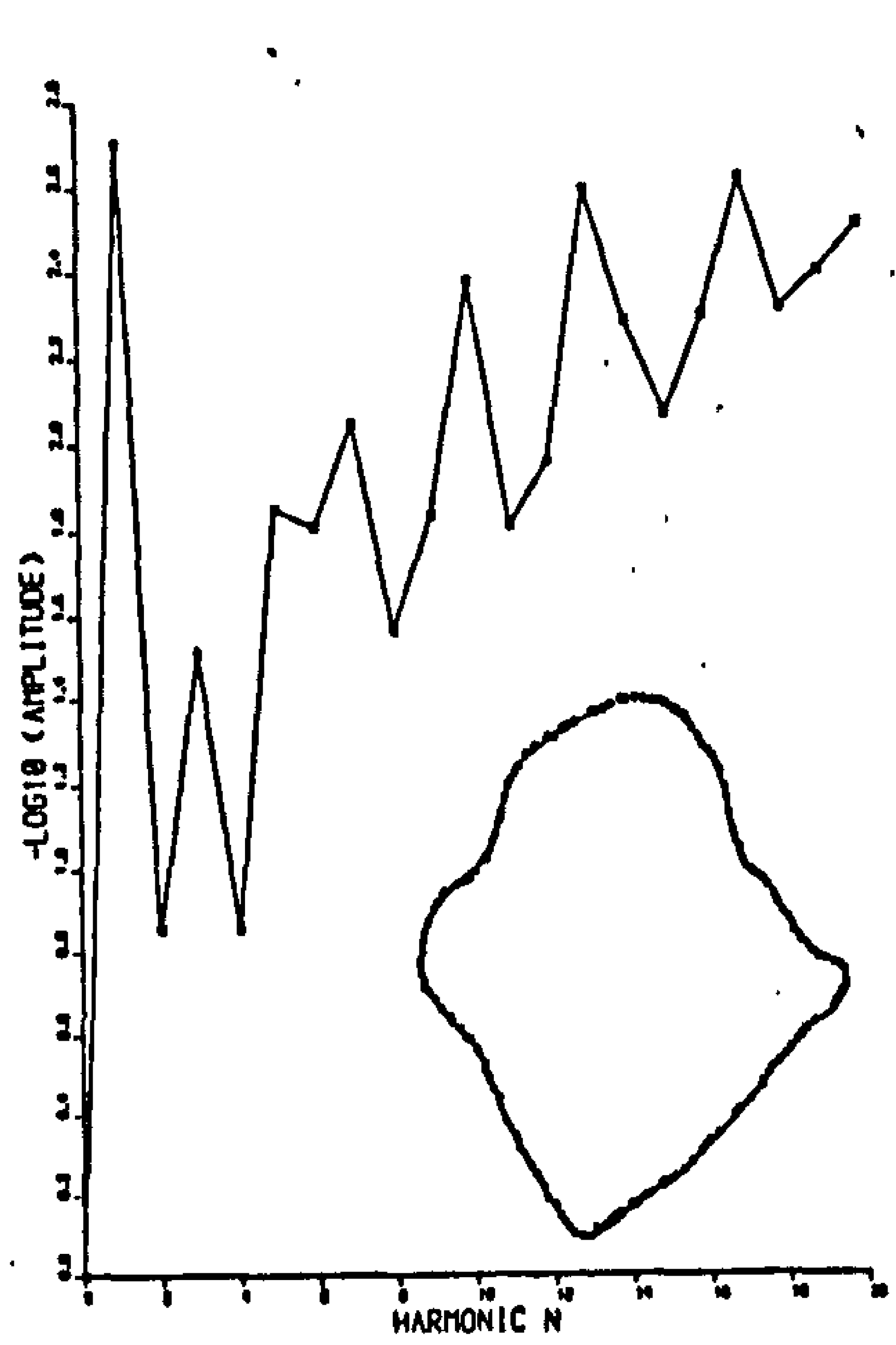
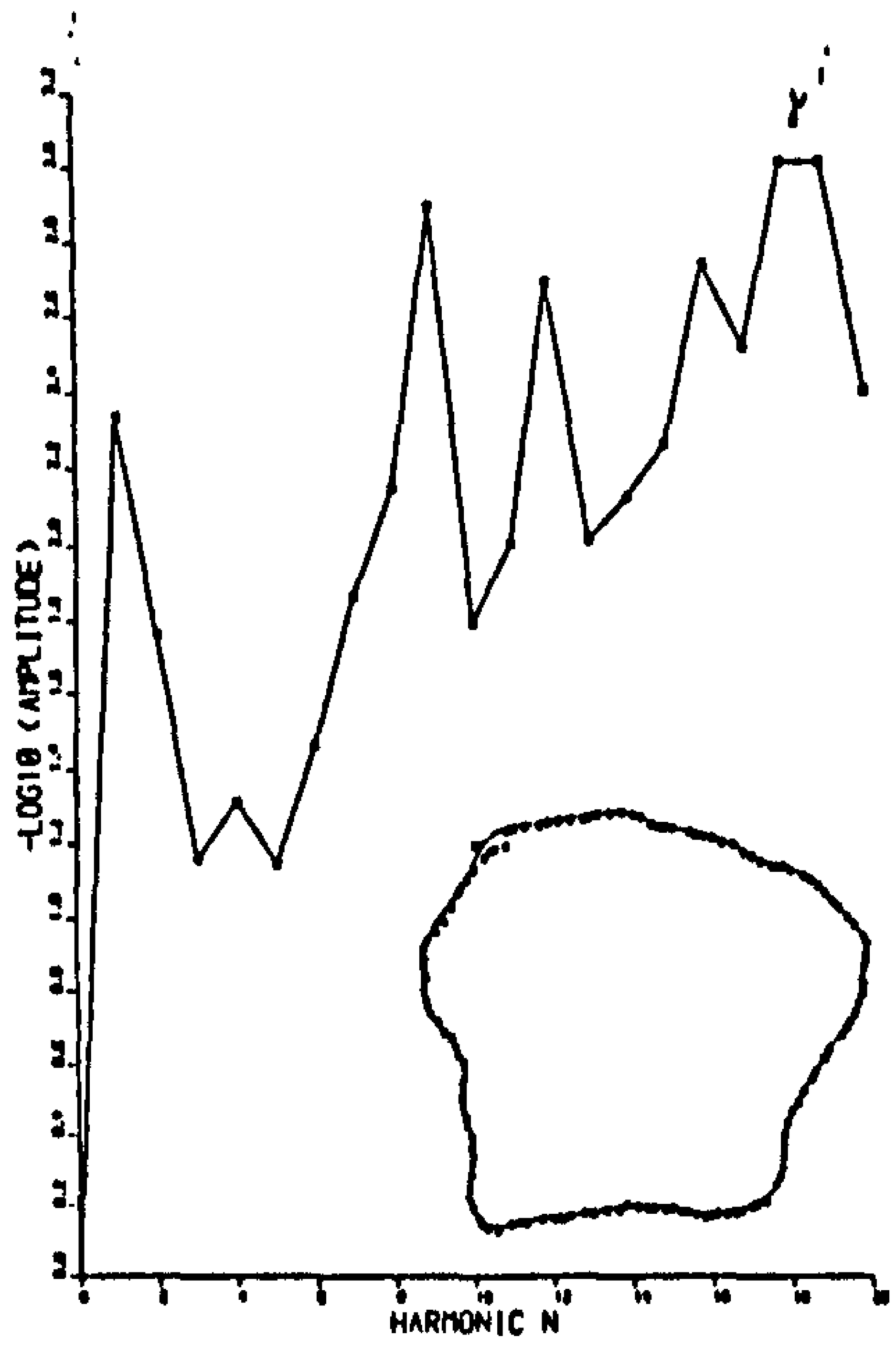


VISS ROCK 3



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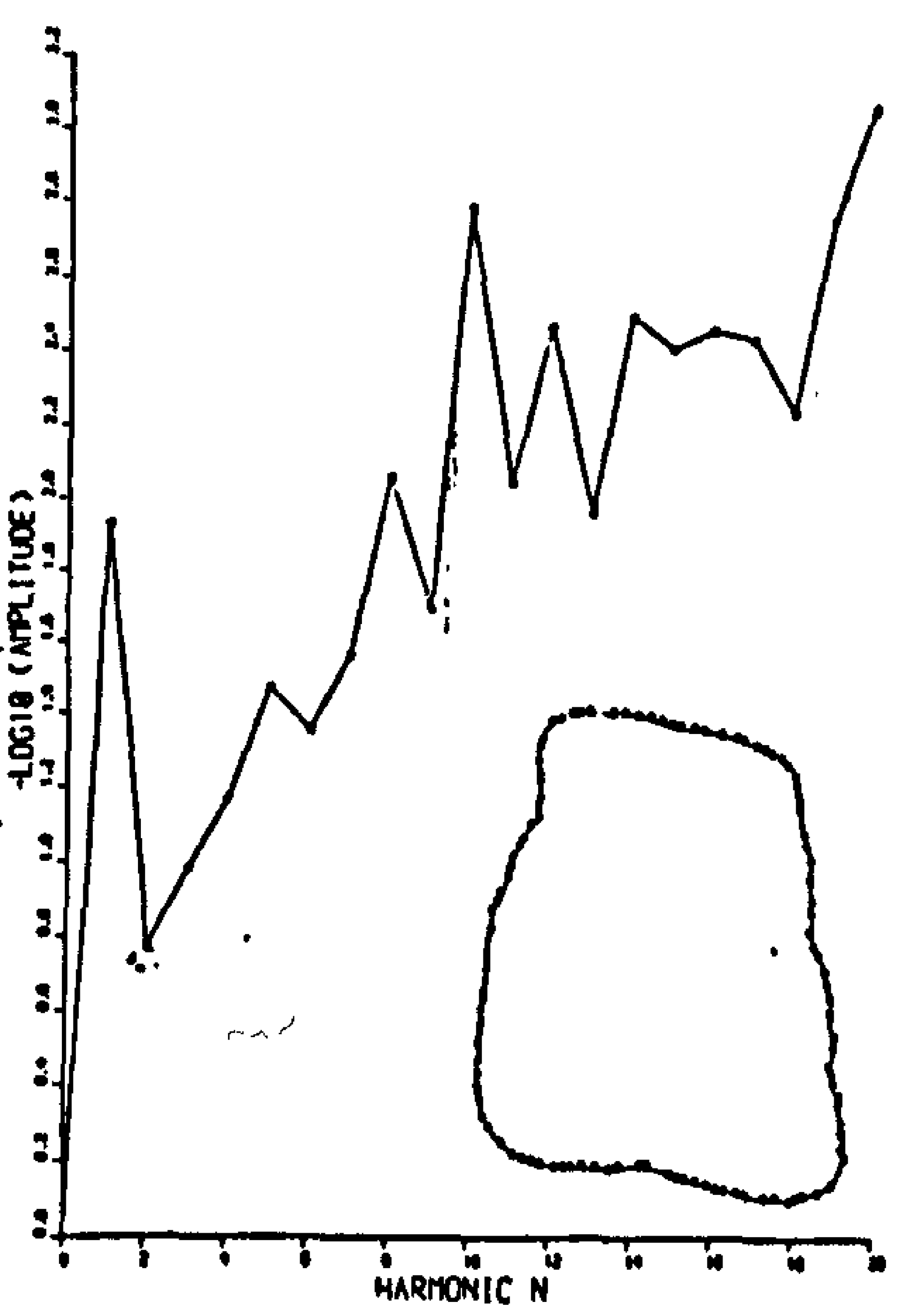

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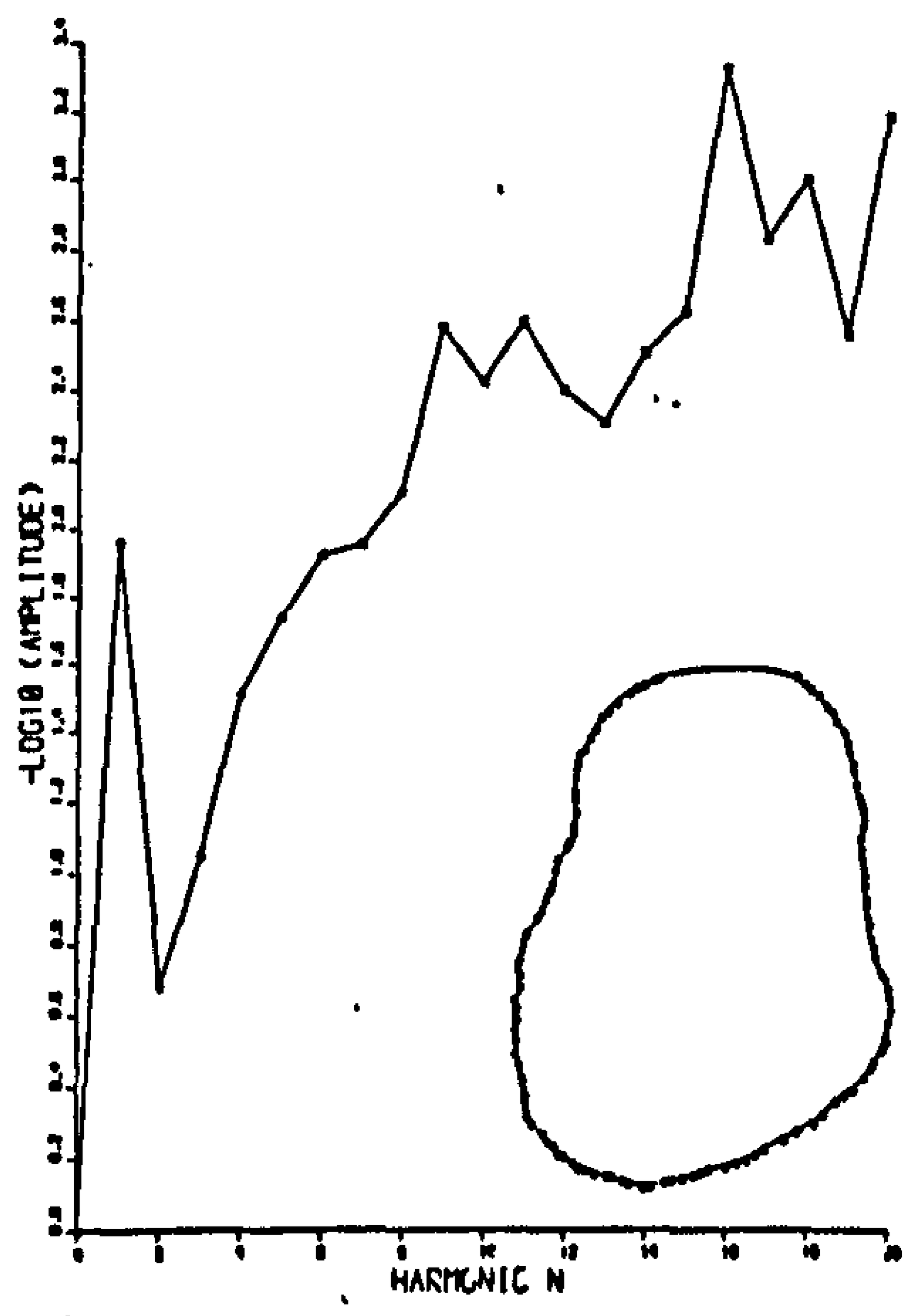

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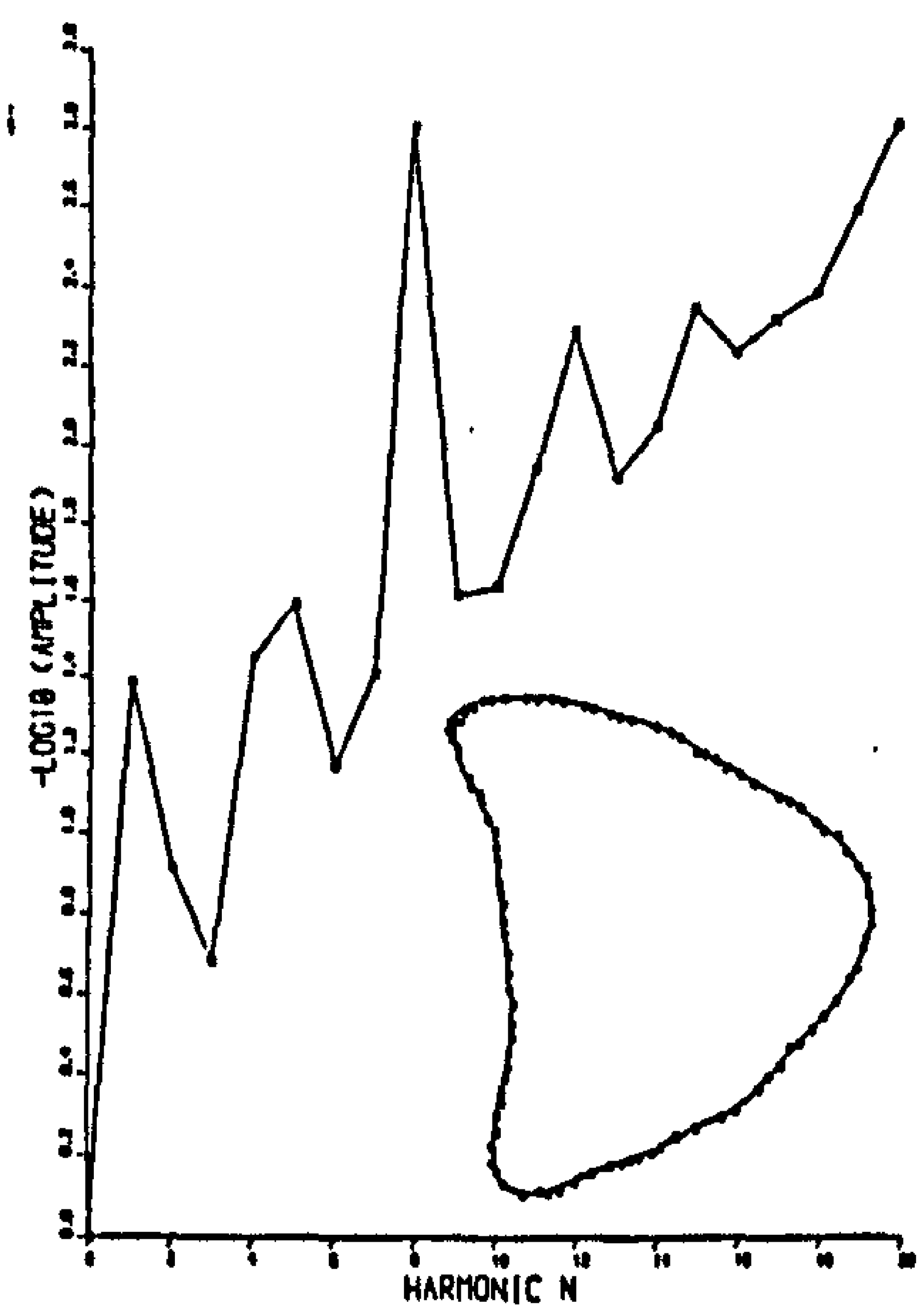

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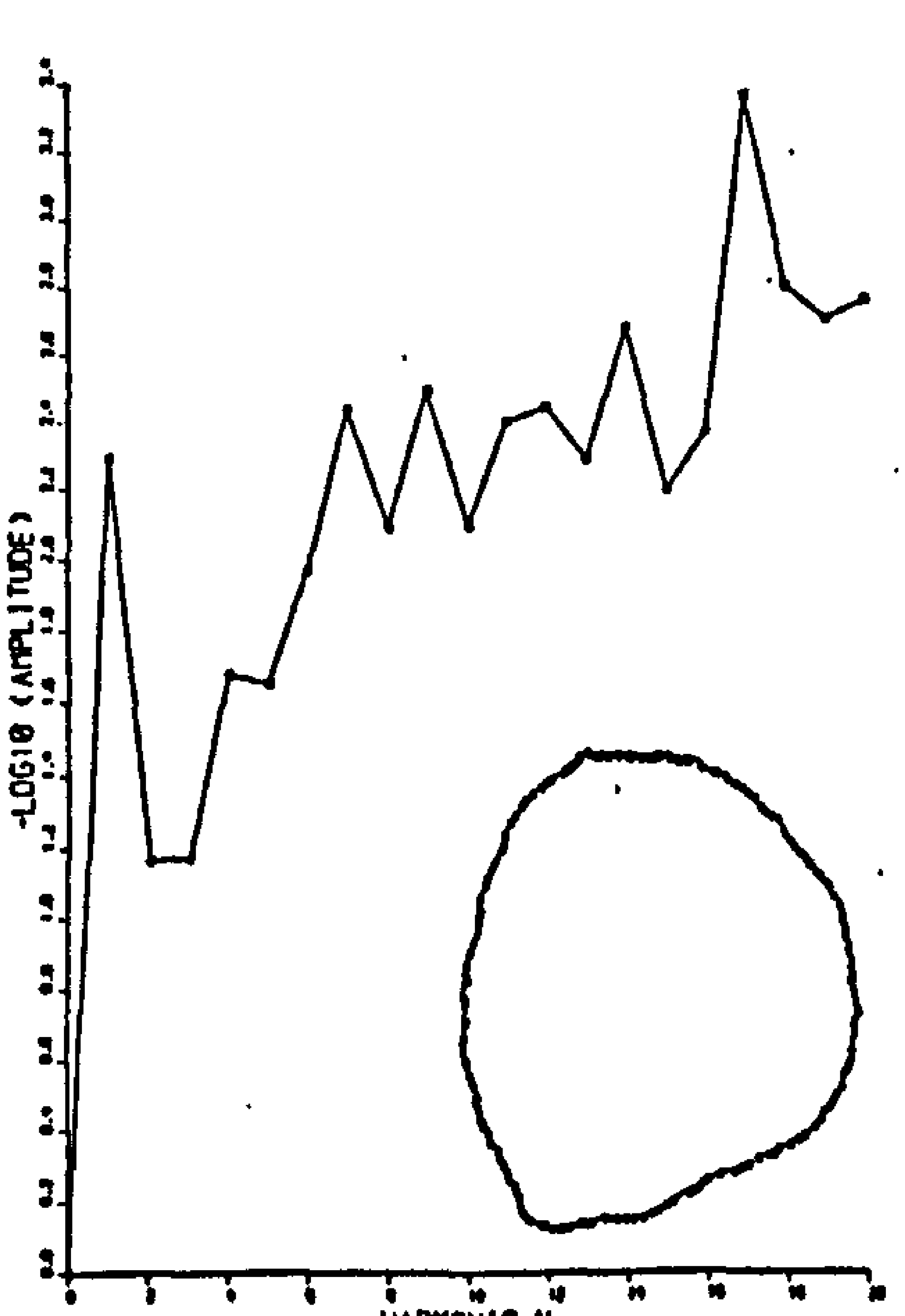
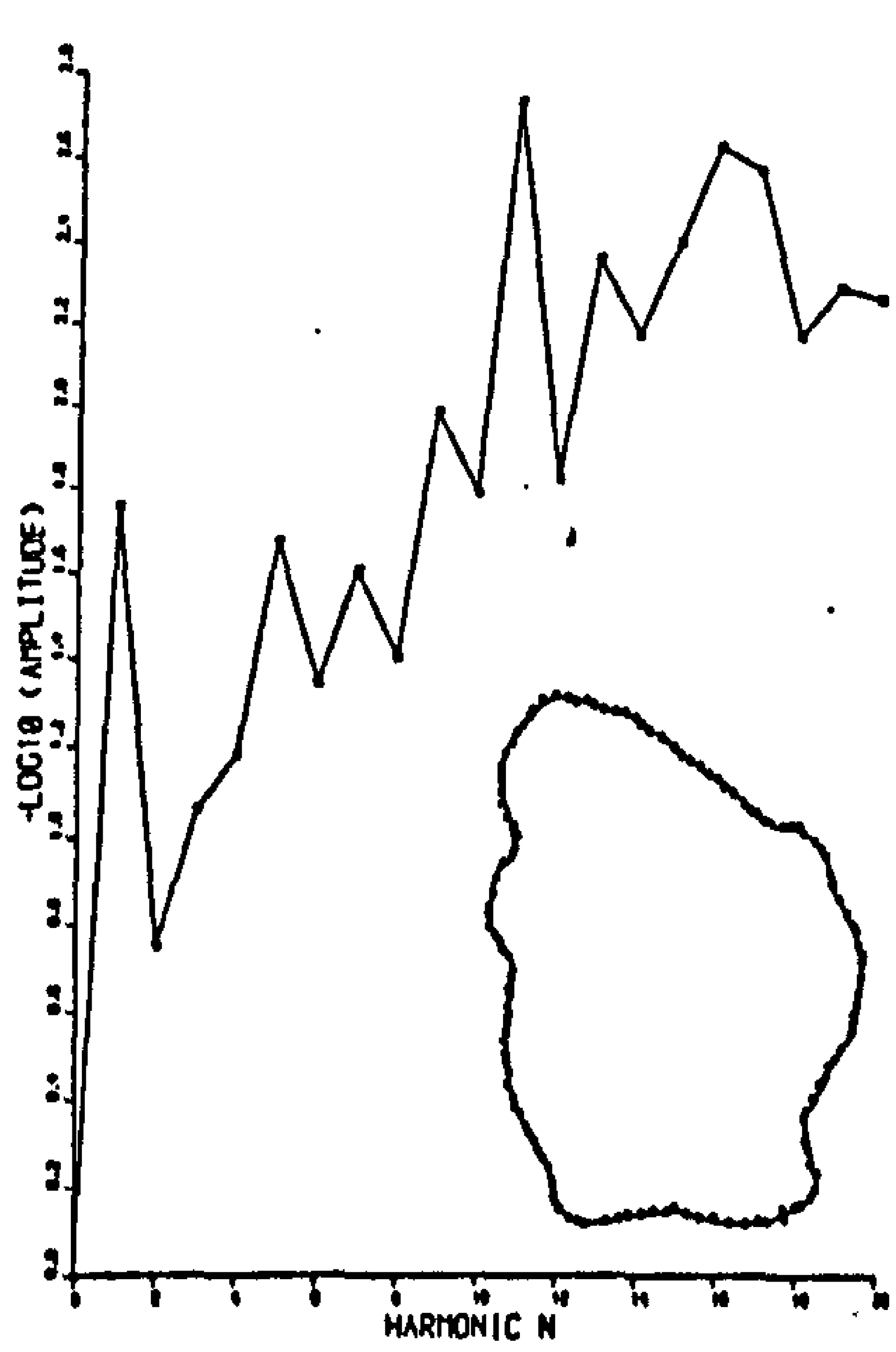


VISS ROCK 8



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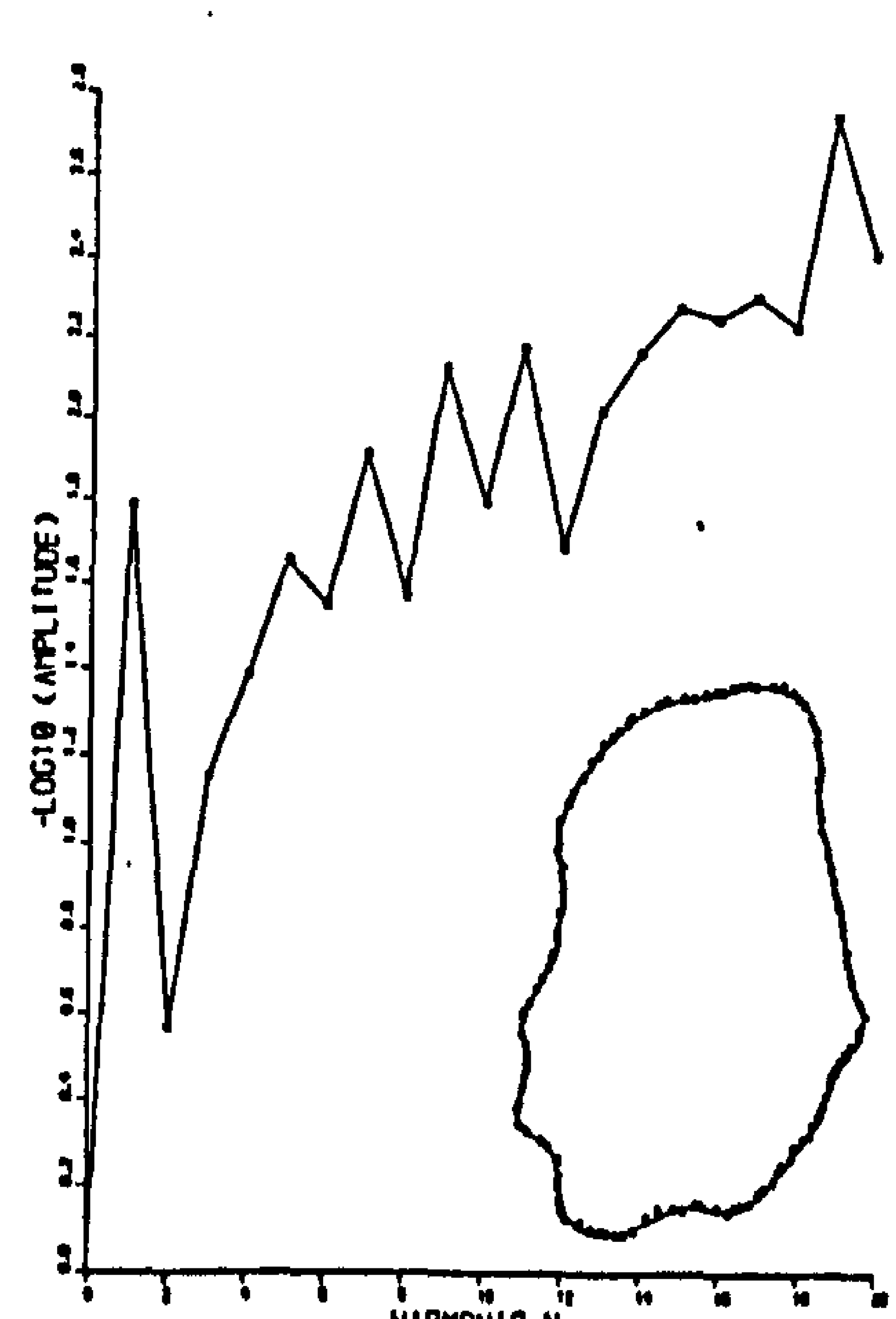

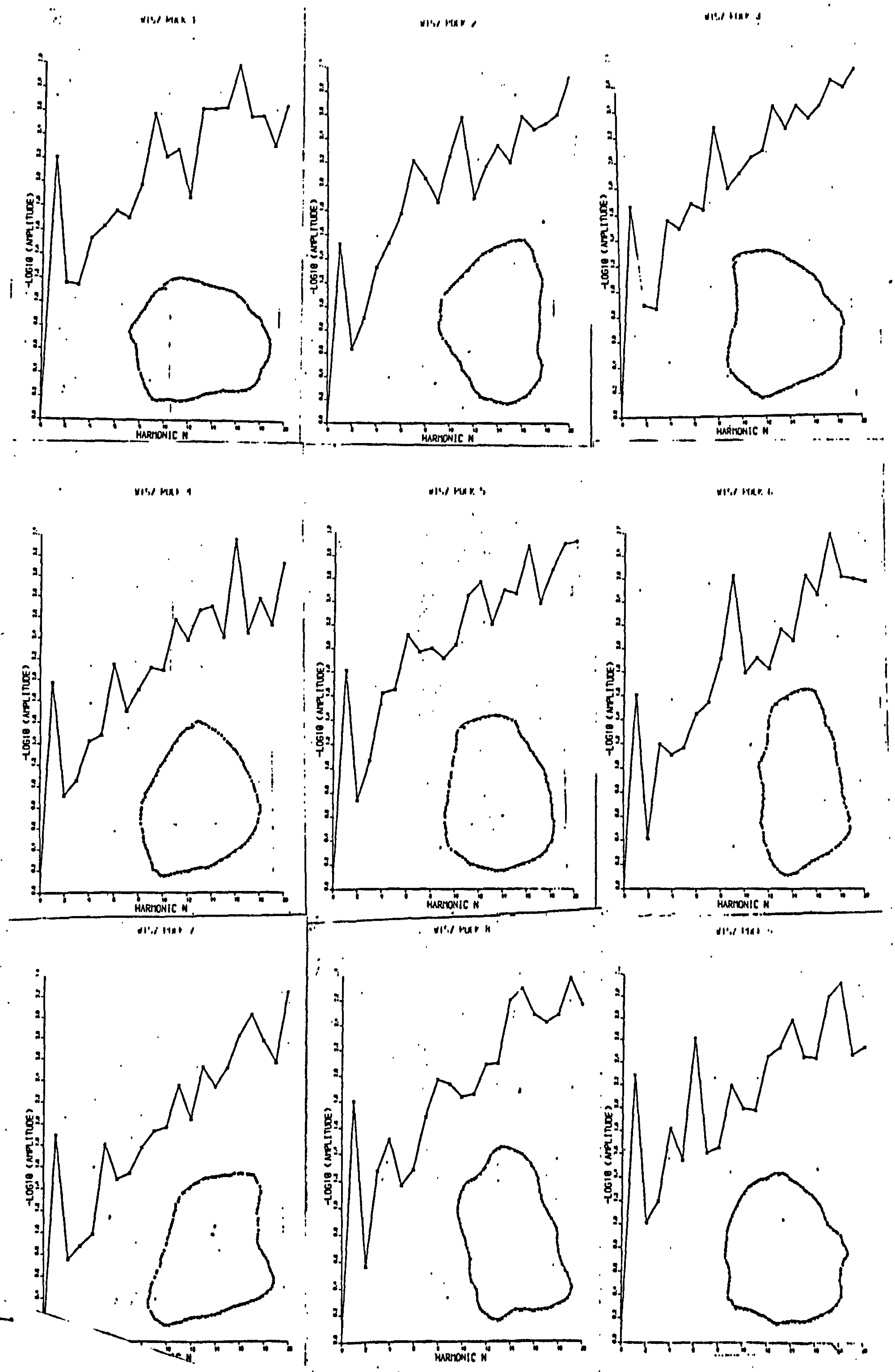
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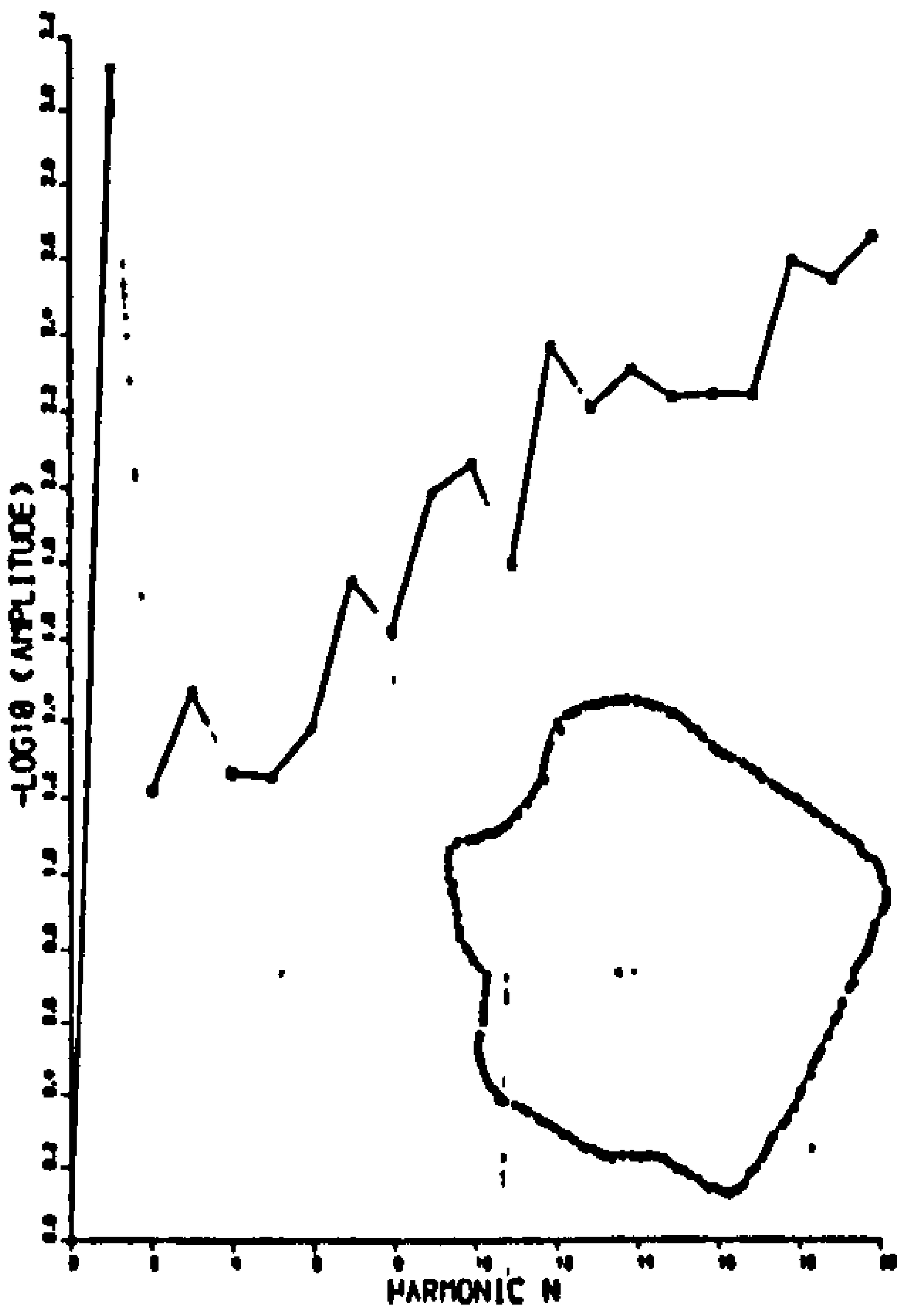
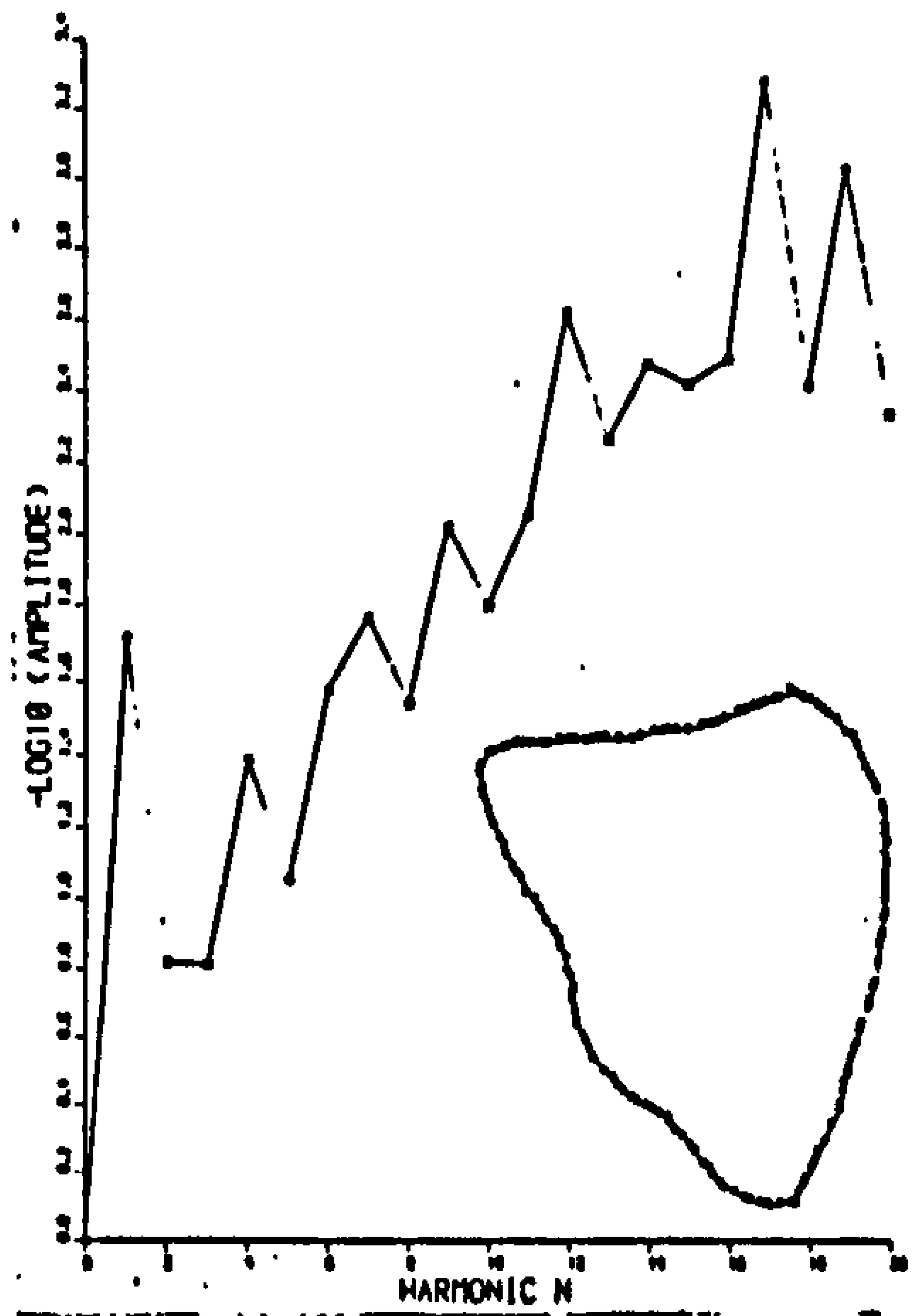
WIS8 ROCK1



WIS8 ROCK2



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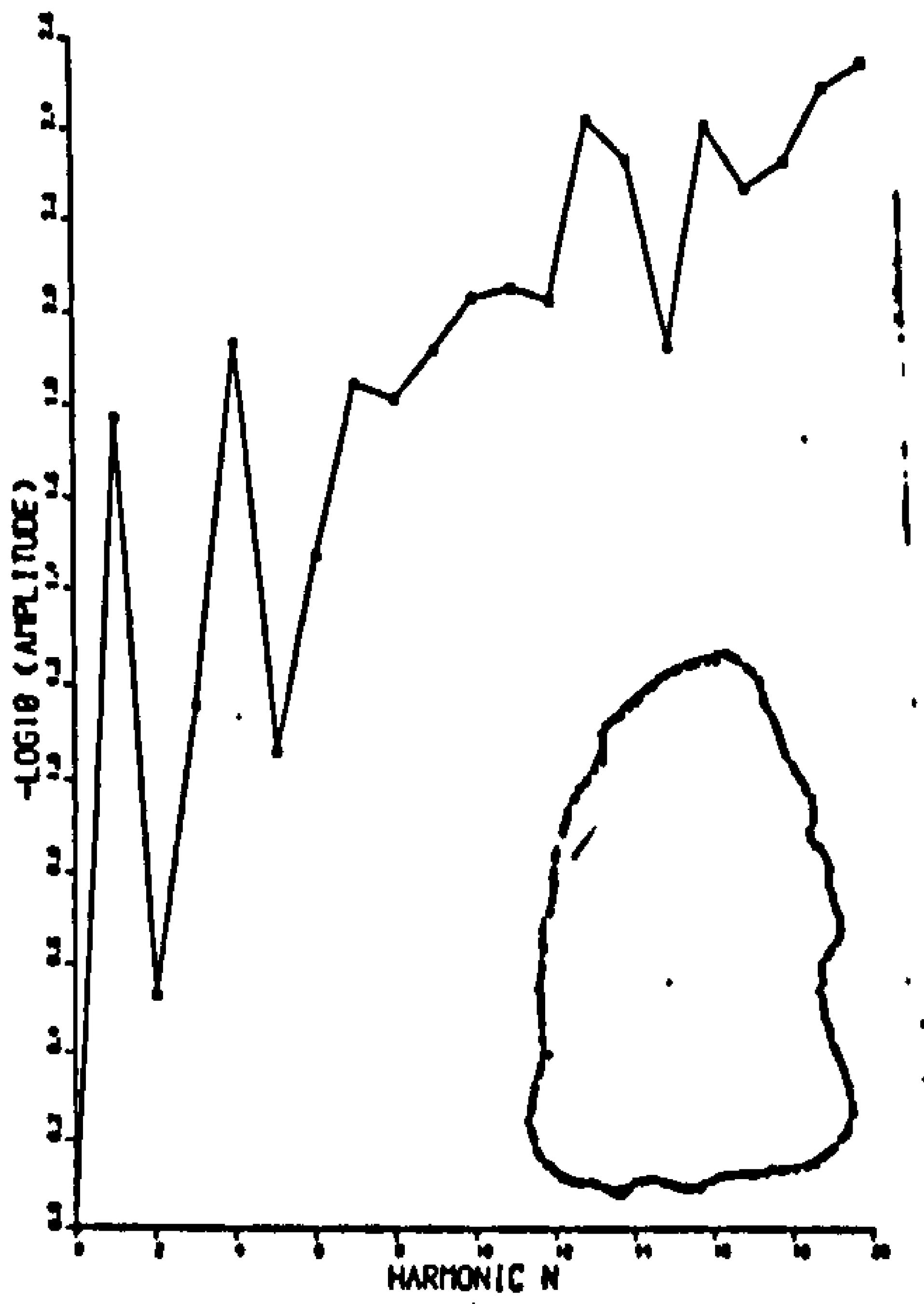

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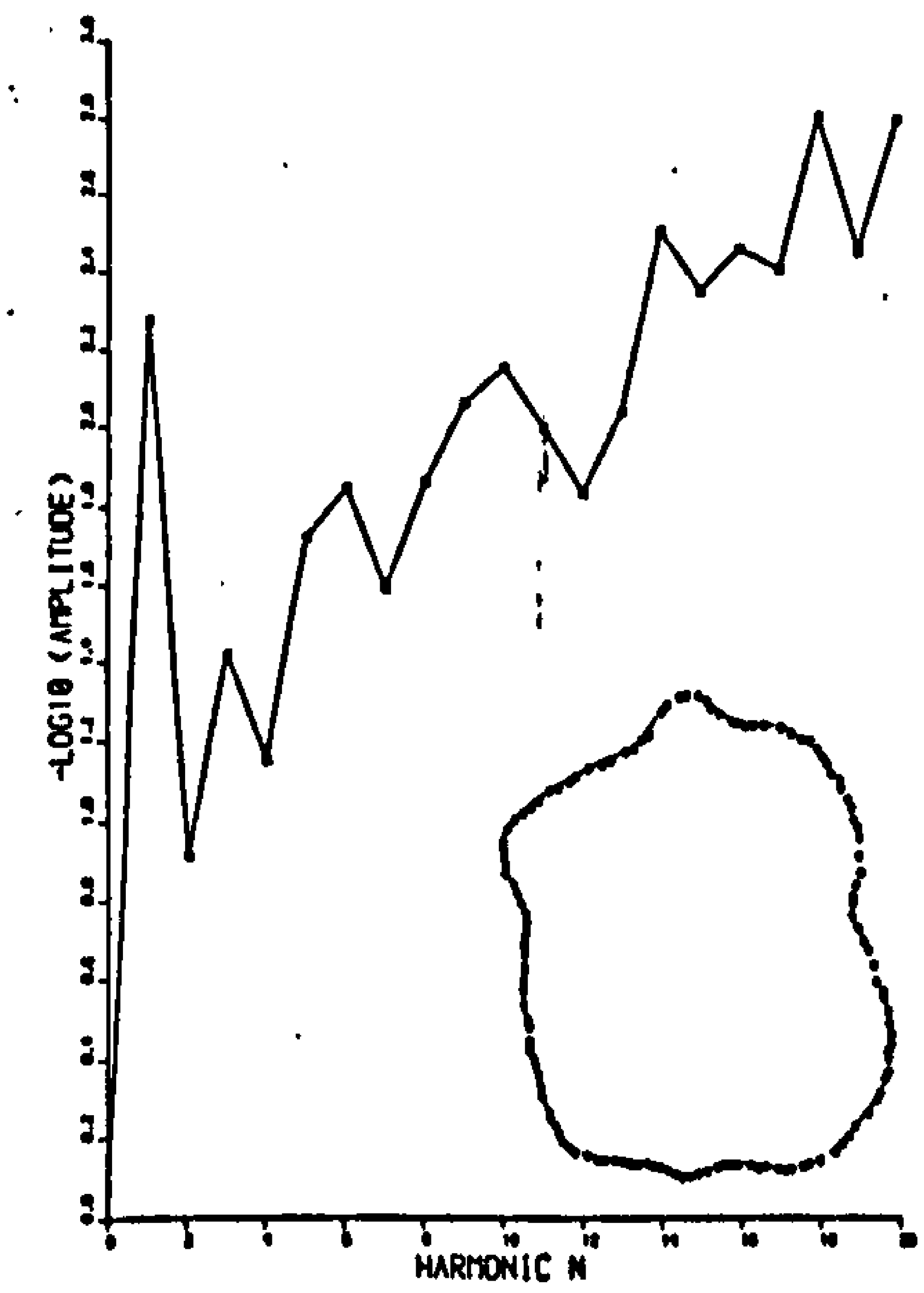

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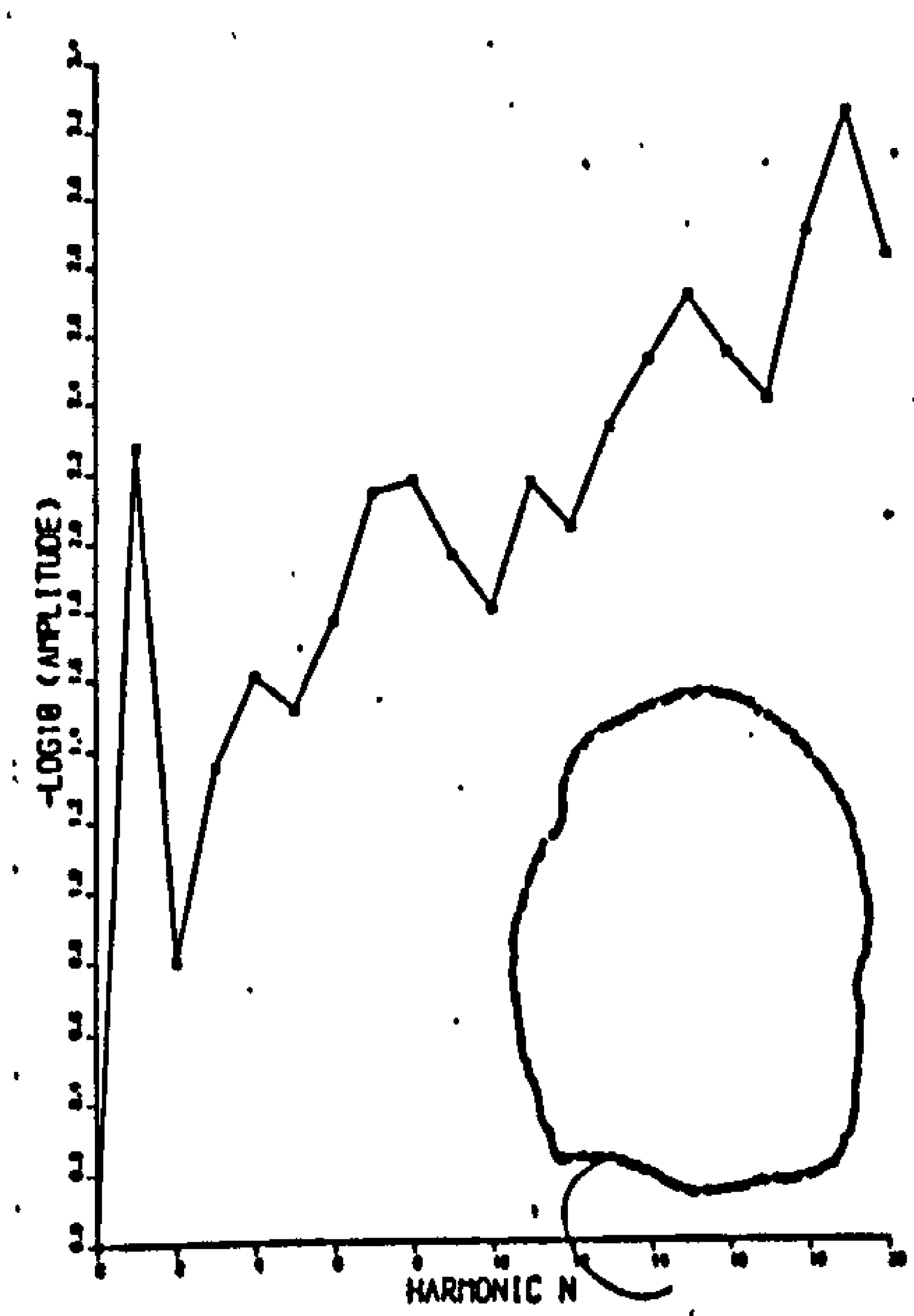

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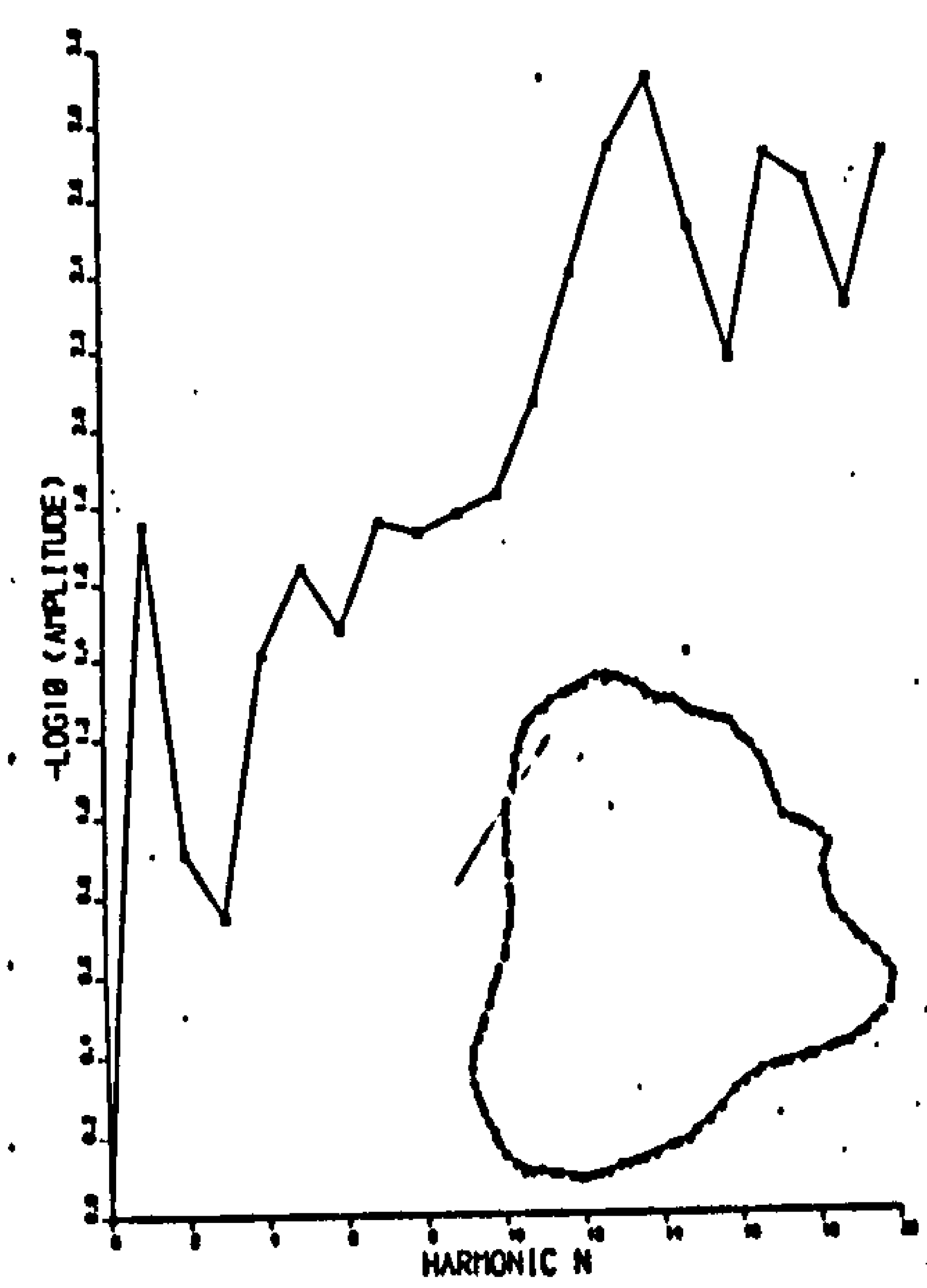

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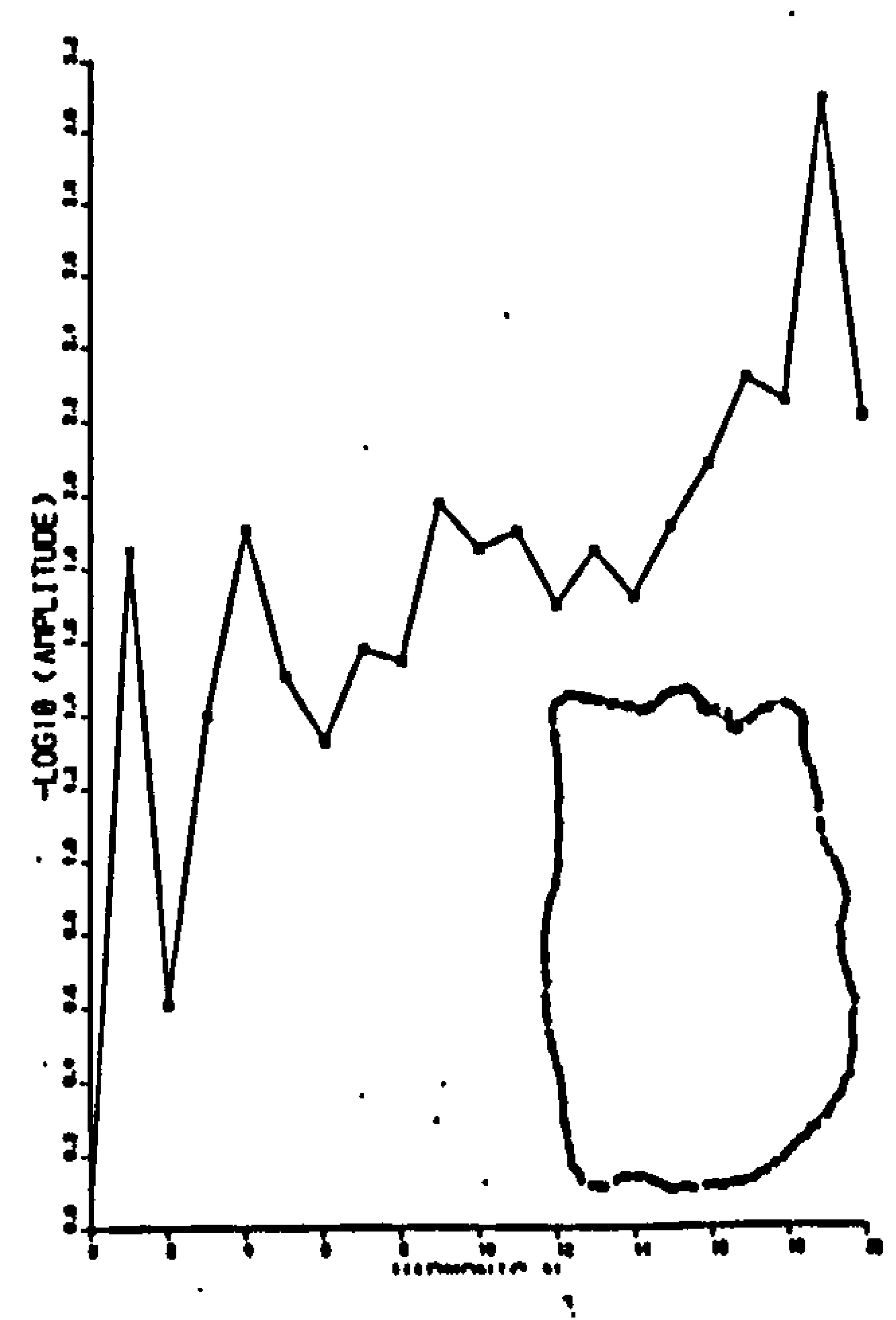
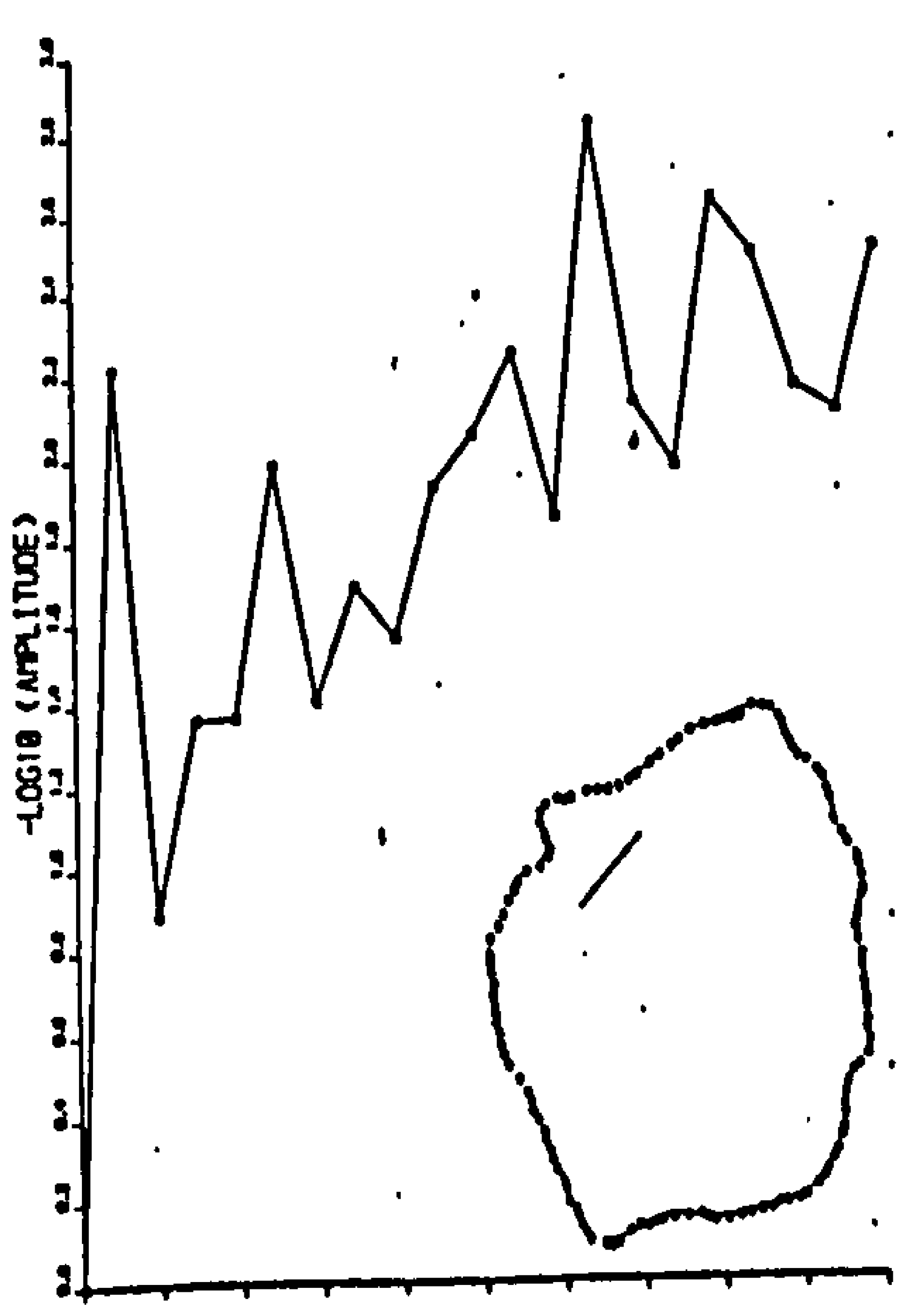


WIS8 ROCK 8



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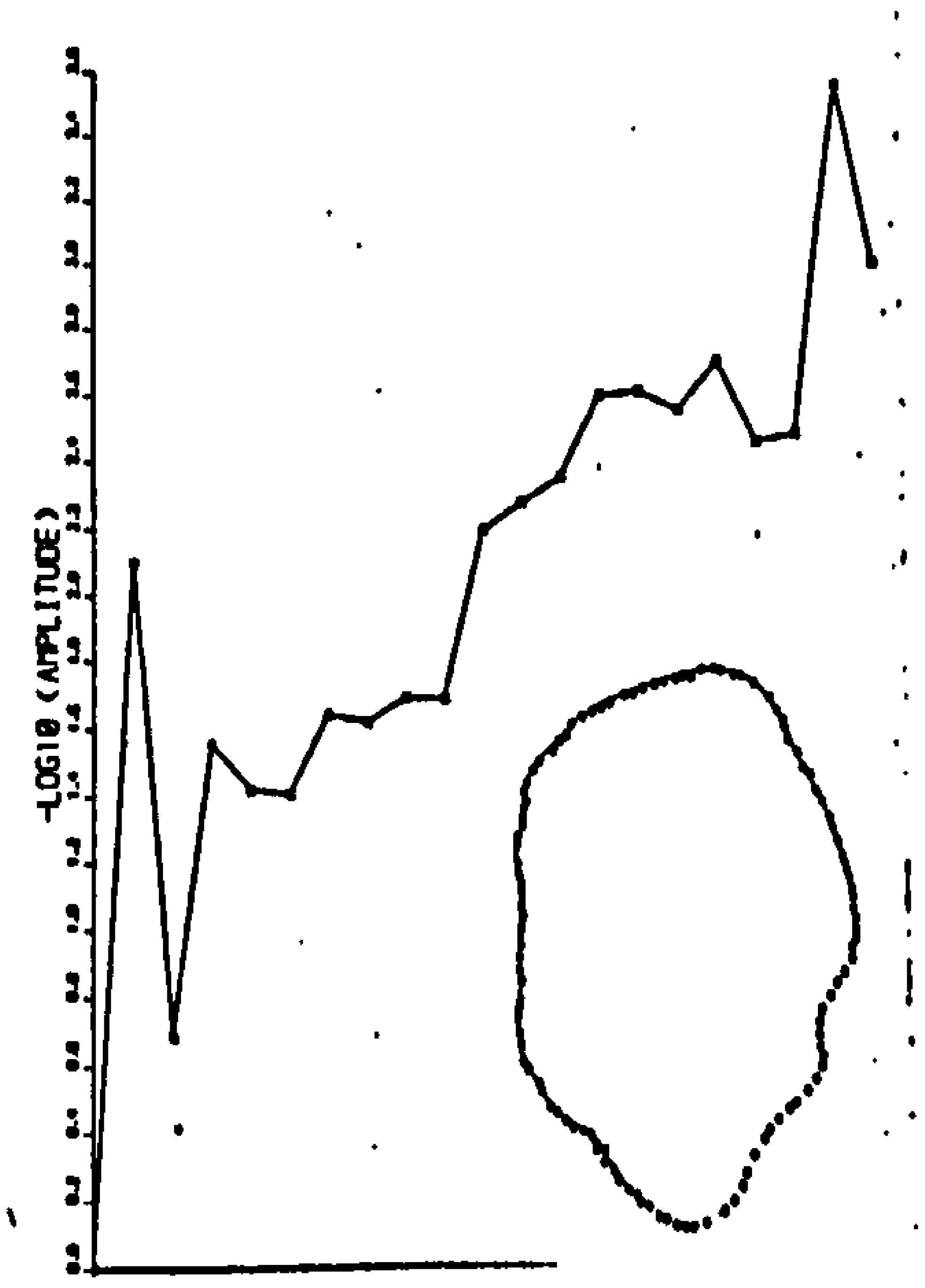

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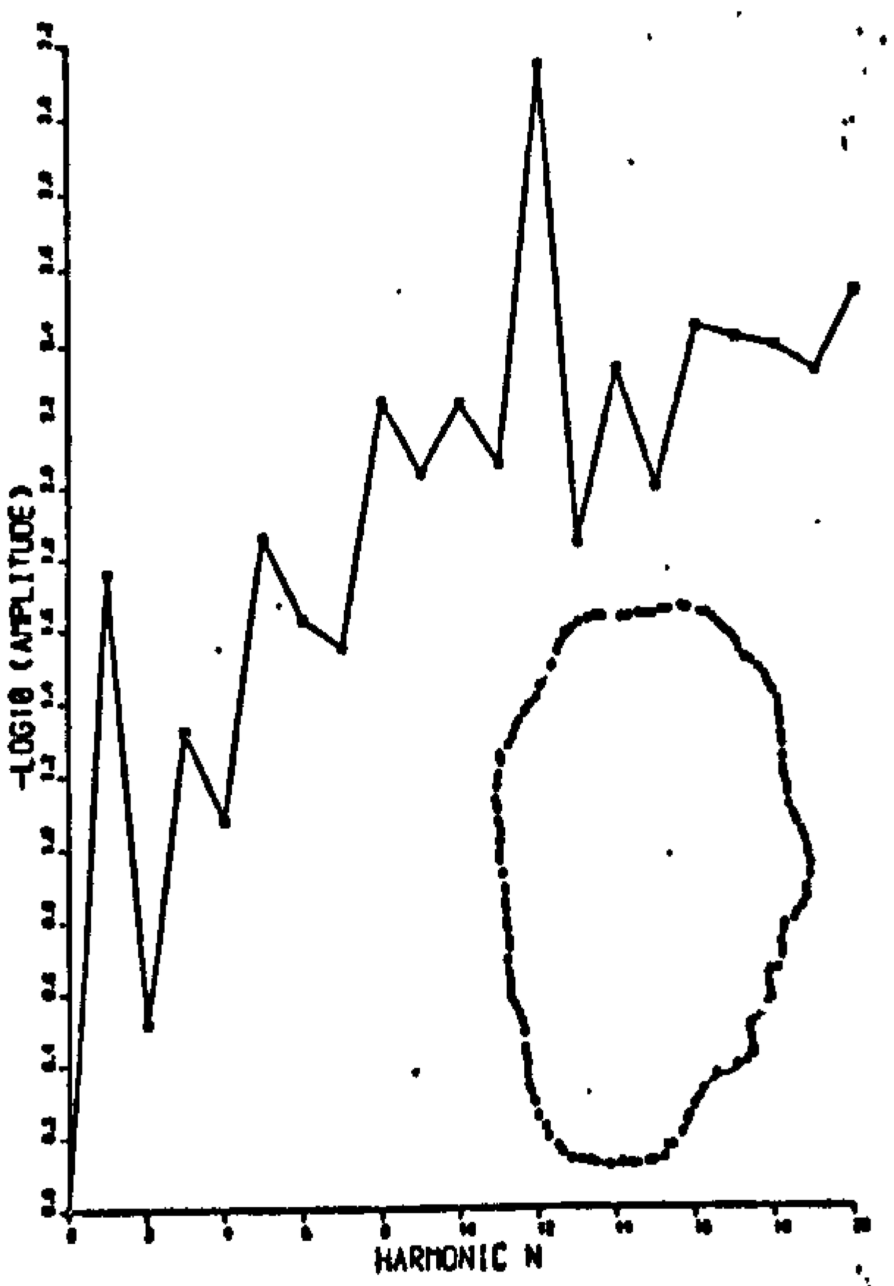

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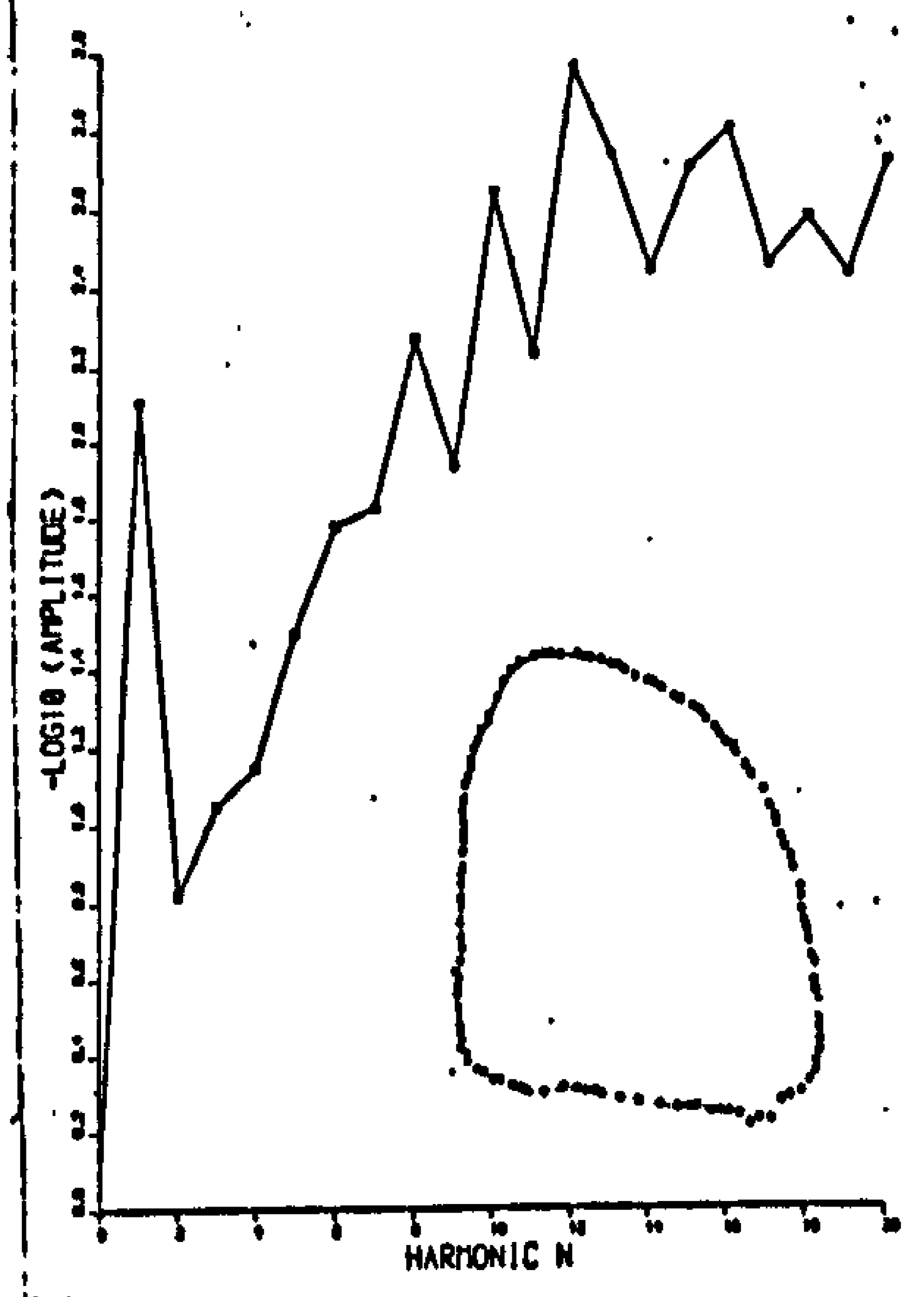

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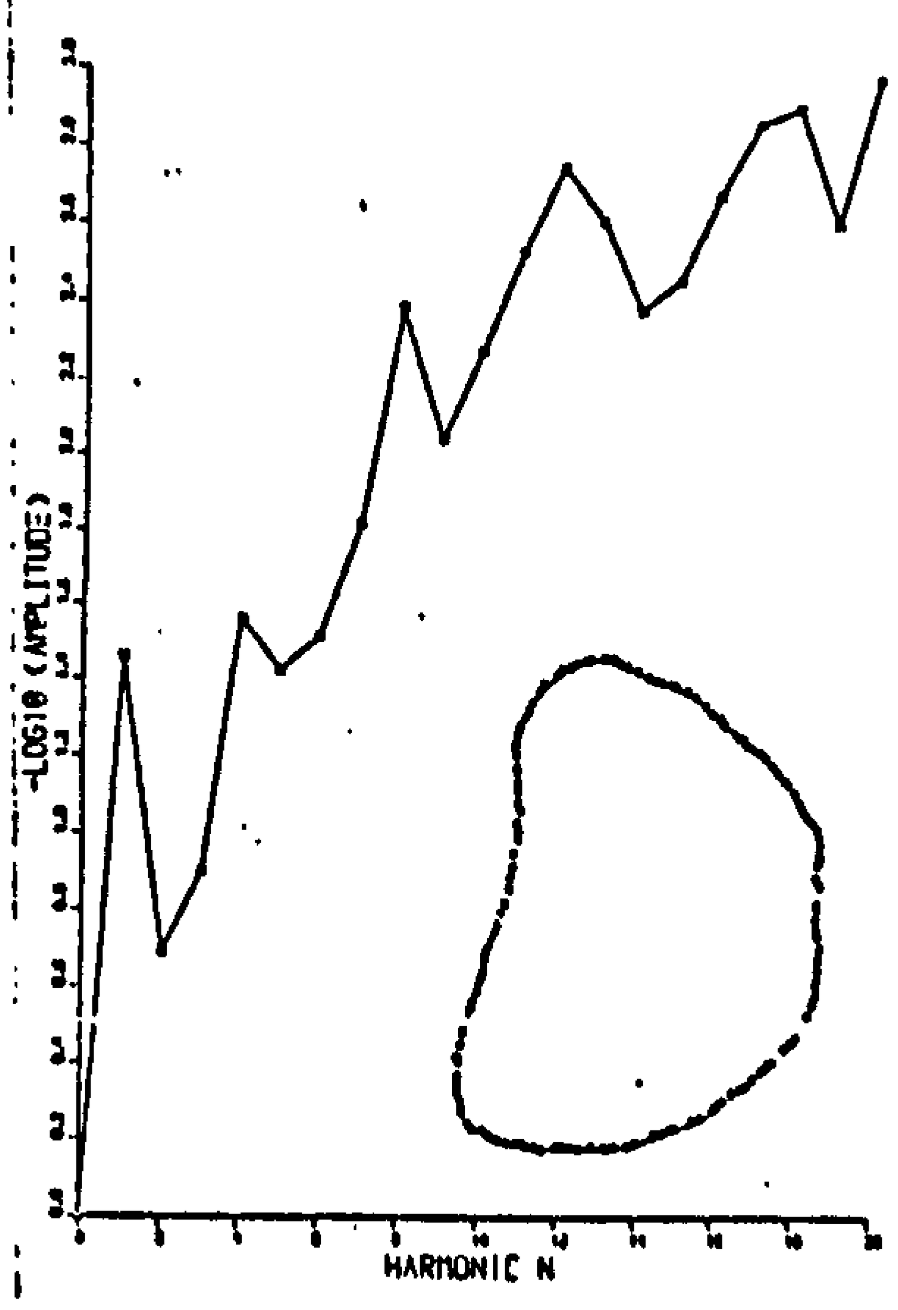
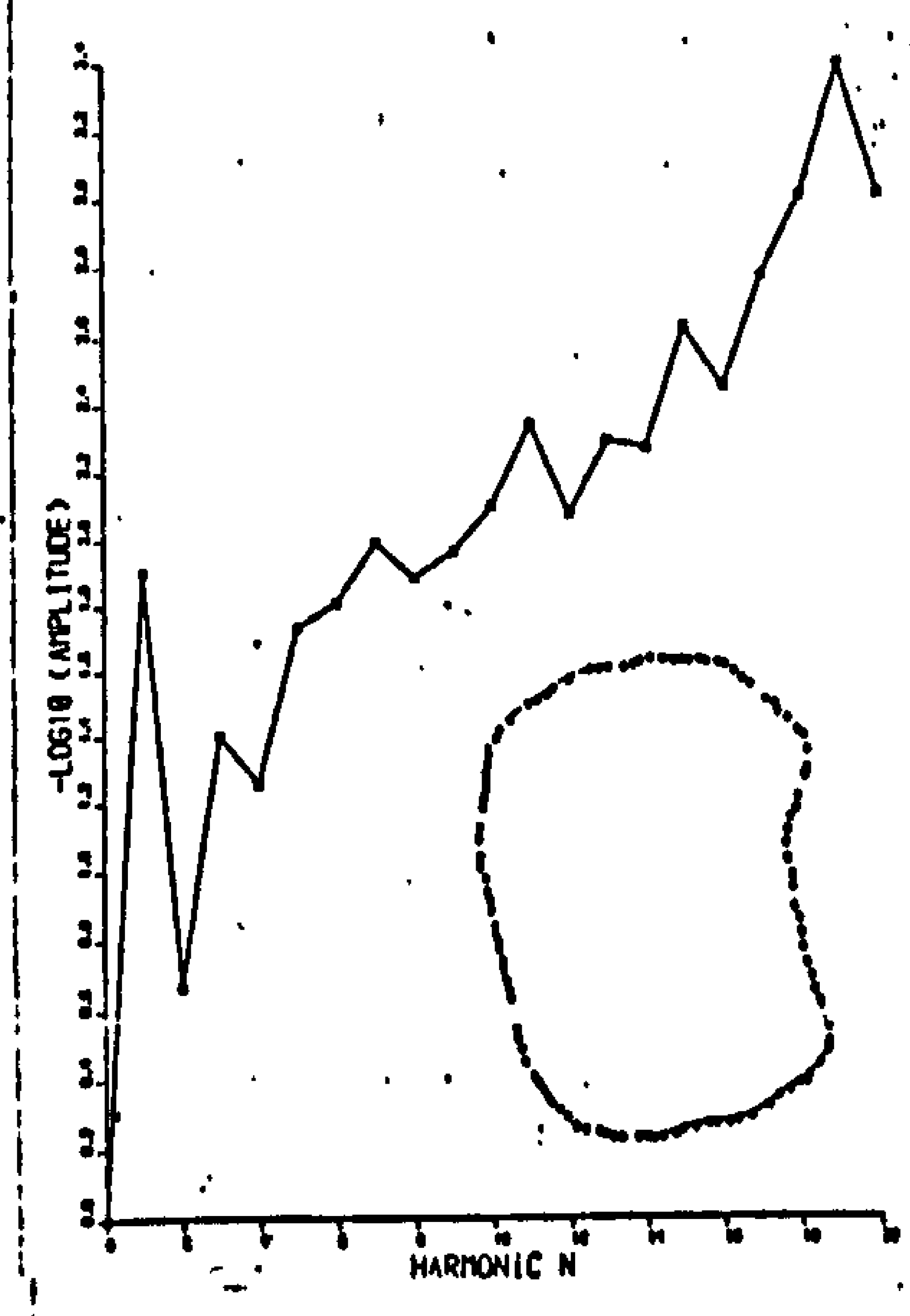


VIS9 ROCK 4

VIS9 ROCK 5



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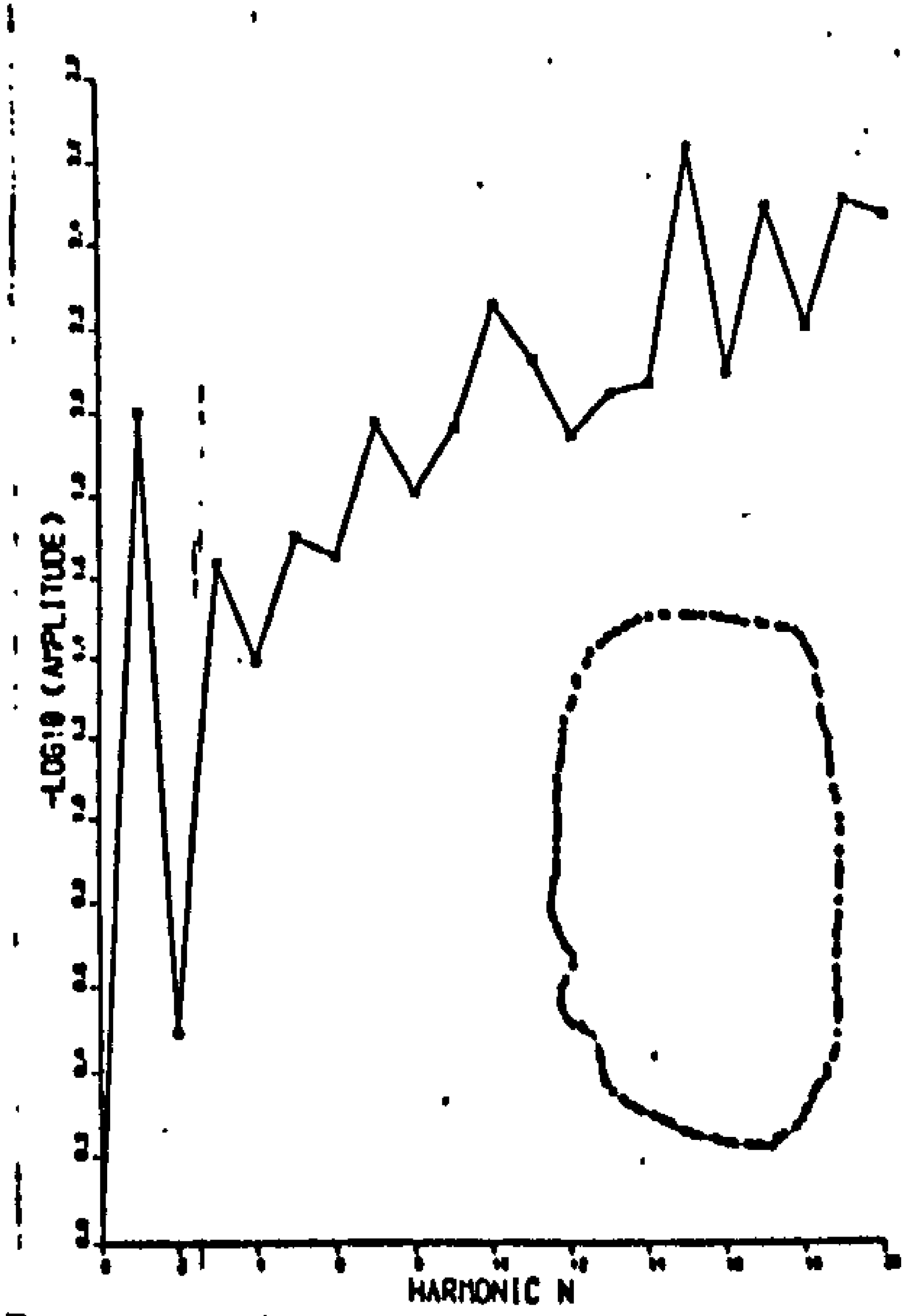

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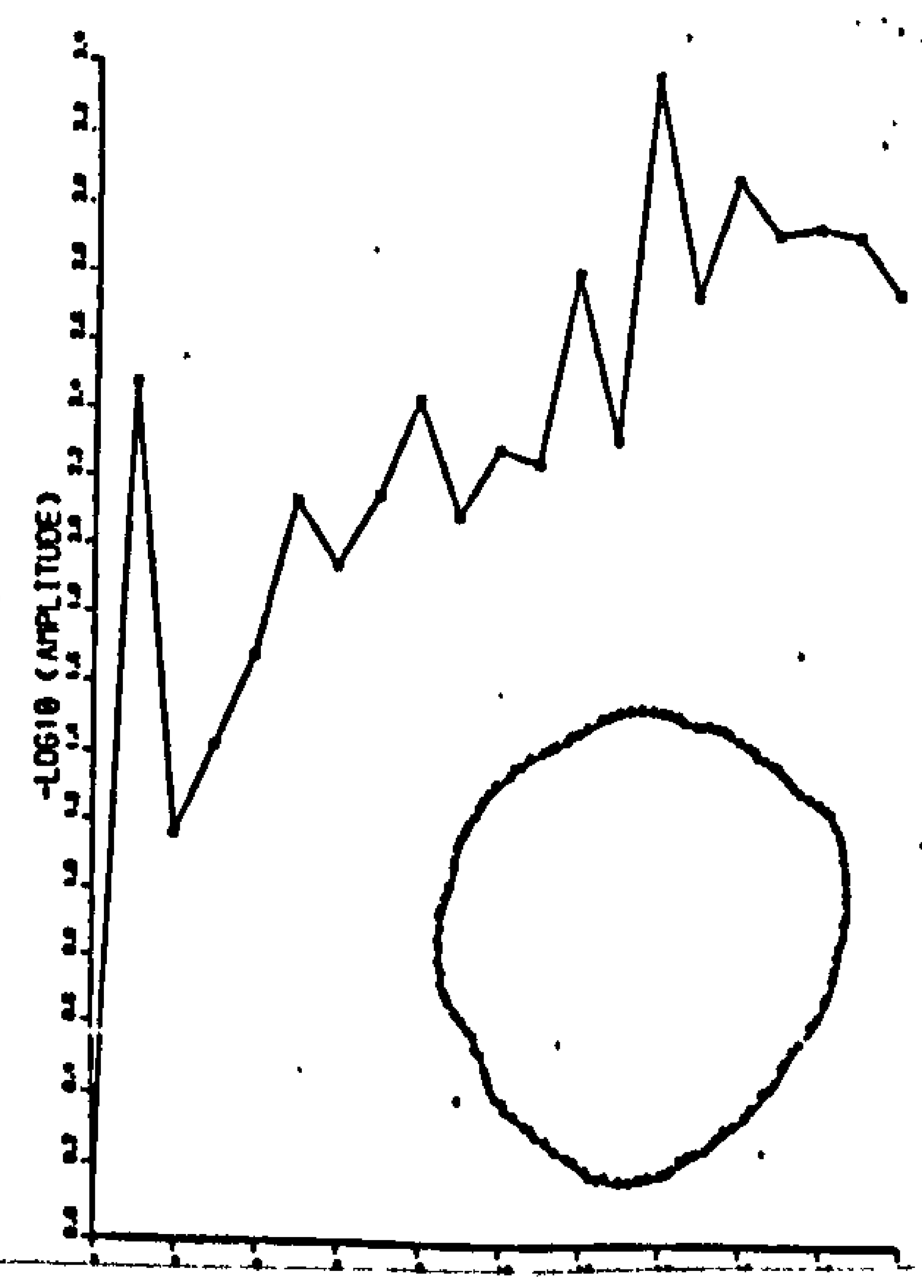

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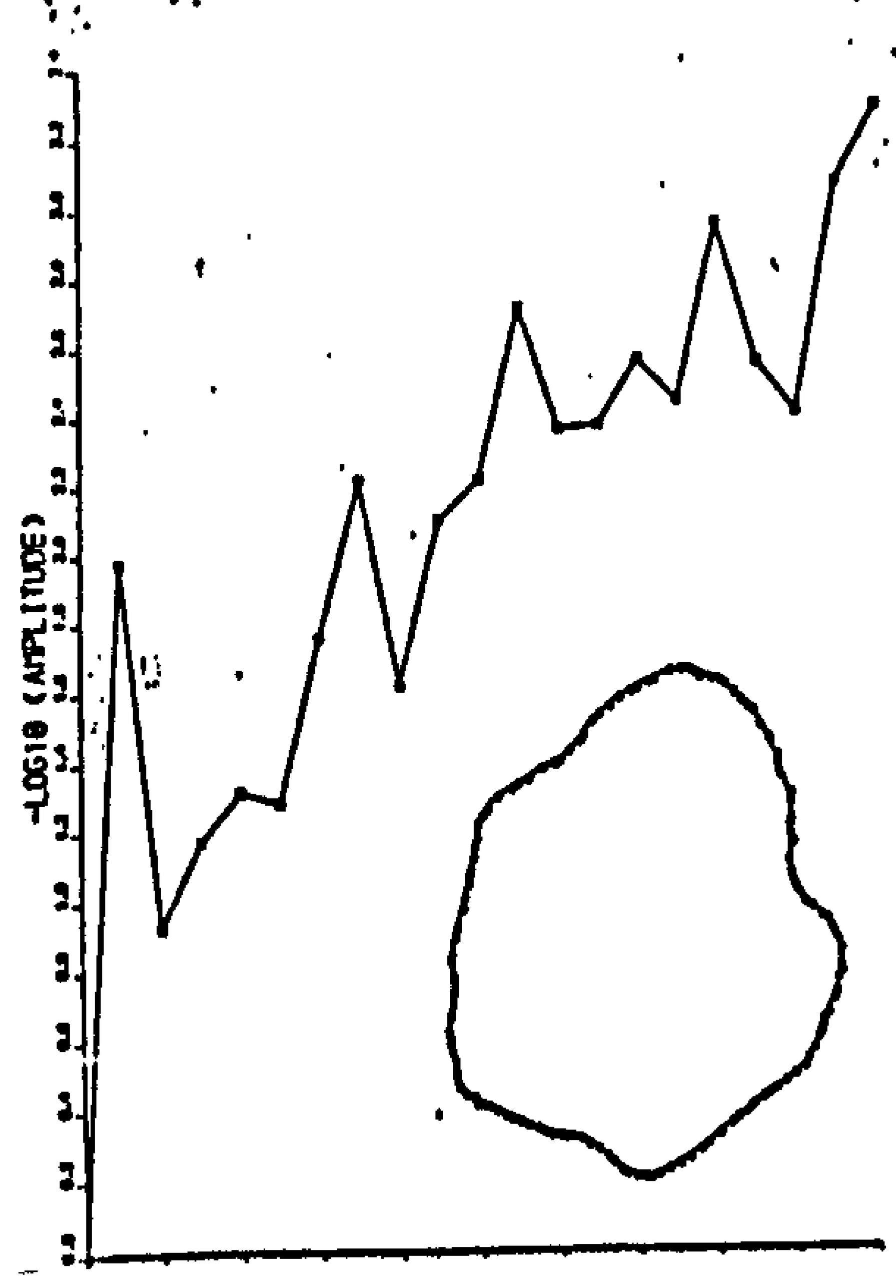

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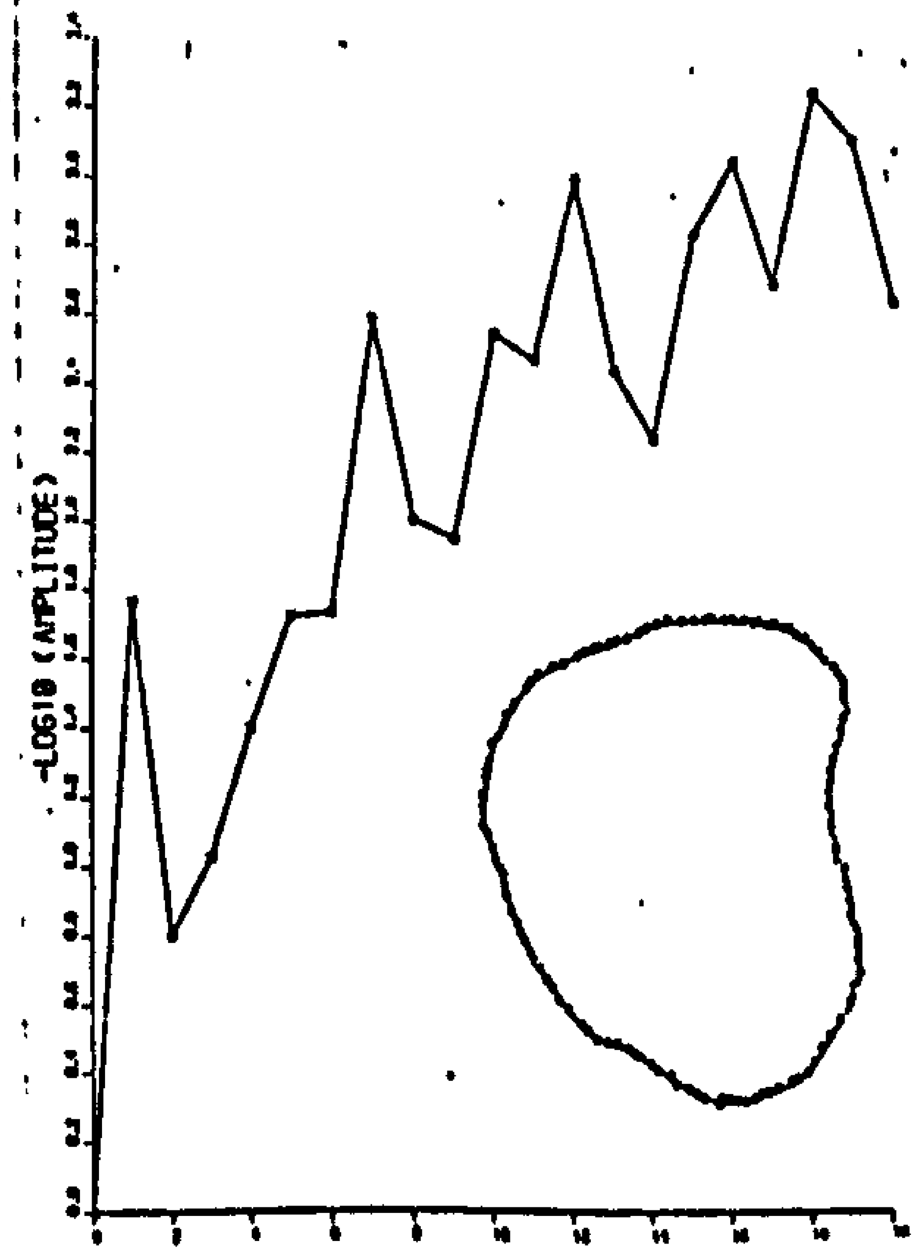

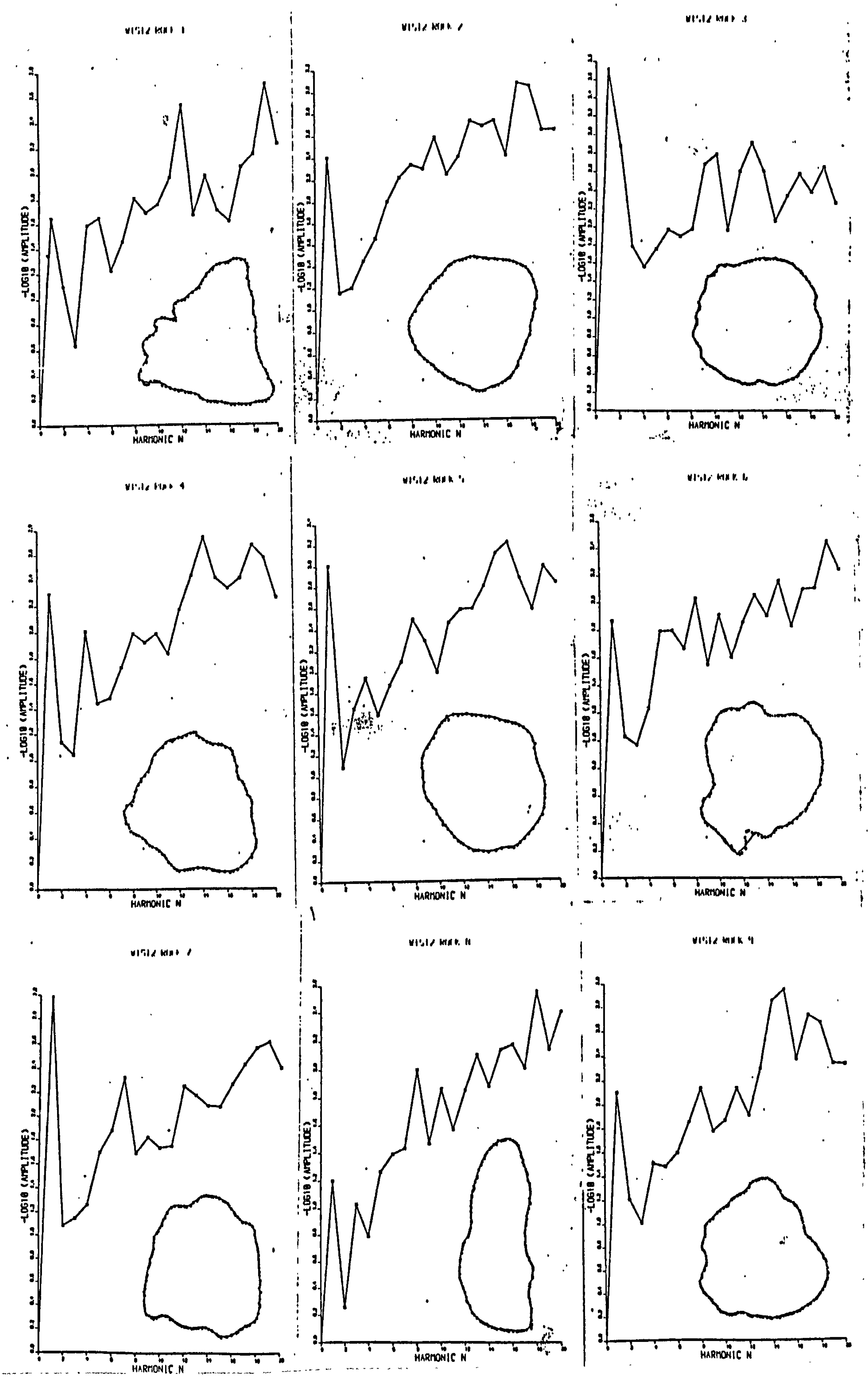
-LOG10 (AMPLITUDE)
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APPENDIX VII

UK SPELEOTHEM URANIUM SERIES DATES.

(Original authors permission should be obtained before quotting unpublished dates. See end of appendix for addresses.)

MEAN AGE	+1 SD	-1 SD	238U/ 234U RATIO	230Th 232Th RATIO	LAB. No.	LOCATION, REFFERENCE AND ADDITIONAL INFORMATION.
11000	6000	6000	2.070	52	GB1A	G.B.CAVE,MENDIPS.
8000	1000	1000	2.400	29	GB1B	ATKINSON ET AL 1978
63000	19000	19000	2.110	114	GB1D	
13000	3000	3000	2.560	25	GB1E	
127000	25000	25000	1.710	20	GB20-1	
63000	11000	11000	2.410	13	GB23A	
322000	250000	100000	1.220	999	GB24/	
172000	26000	26000	1.360	501	GB27-I	
290000	250000	80000	1.330	999	GB10A:1	ATKINSON + SMART UNPUBLISHED
58700	2100	2100	1.723	62	GB14B	
220000	130000	50000	1.230	12	GB17:2	
228000	13500	12000	1.970	999	GB21:1	
170000	15500	13900	1.974	83	GB21-2	<10% Th YIELD
22900	1500	1500	2.469	124	GB22A	10% U YIELD.
111800	10400	9700	2.023	14	GB23 14A-1	
70300	6300	6100	2.469	11	GB24-1	
135400	22000	18700	1.528	20	GB24-2	
313000	51400	47800	1.517	272	GB27II-2A	
123000	5300	5100	2.159	29	GB28B-1	
114700	5600	5300	2.105	999	GB28B-2	
103400	6500	6200	2.409	43	GB32B-1	
88400	4100	4000	2.556	85	GB32B-2	
98000	4800	4600	2.367	314	WHOLE ROCK	
73300	4200	4100	1.930	389	GB33TP	
77500	3500	3400	1.945	16	GB33BT	
93100	5400	5200	2.391	30	GB34TP	
94100	4400	4300	2.248	33	GB34BT	
59200	2800	2800	1.637	11	GB34A-TOP	
56800	1600	1600	1.704	41	GB34A-B	
55400	1800	1800	1.723	35	GB35-1	
58100	2500	2400	1.680	145	GB35-1(RPT)	
59300	2100	2000	1.724	43	GB35-2	
59400	1900	1900	1.729	141	GB35-2B	
69700	6100	5800	1.686	41	TAPS 35-03	
5000	200	200	2.859	55	GB40-1	ATKINSON ET AL 1986
8700	500	500	3.103	42	80011-3ST	
3700	400	400	2.876	114	80011-3BM	
800	100	100	2.676	40	80011-3TP	
98000	8000	8000	1.960	23	GB42	
12800	2600	2500	3.499	25	780527 BTM	<10% U+TH YIELD.
8500	1700	1700	3.284	37	780527 MID	
2700	3000	2900	3.502	999	780572 TOP	<10% TH YIELD.
11800	1100	1000	3.374	999	780527 O2R	
9400	300	300	2.381	999	GB39	
9500	400	400	2.531	999	GB38-I	
7100	200	200	2.335	999	GB38-0	
7000	500	500	1.720	21	GB37	
9000	2500	2500	2.490	999	GB29	ATKINSON + SMART UNPUBLISHED

106600	6600	6200	2.018	20	GB23B	
117500	5600	5400	2.002	240	GB25-1(BASE)	
11400	600	600	2.876	11	GB26-1	
10500	6000	6000	3.47	194	780527-3/5	
106300	9200	6200	1.040	42	SNH52C	SUN HOLE,MENDIPS.
260000	100000	25000	1.150	26	SNH2A	P. SMART UNPUBLISHED
62500	4150	2750	1.150	7	SNH-44A	
41600	5100	4500	1.160	6	SNH-44B	
75100	7400	6500	1.110	4	SNH-44C	
64000	2500	2500	1.070	4	SNH-44D	
123000	3000	3000	1.060	999	SNH-52B	
36000	1000	1000	1.060	23	SNH-52A	
56000	12200	8350	1.100	108	PHI-82B-M	PICKIN'S HOLE,MENDIPS.
82300	19300	12200	1.150	184	PHI-82C-T	
189000	95000	48000	1.120	999	PH1-82-C2	
179000	65000	40000	1.080	184	PH1-82-B2	
166700	42500	27700	1.15	8		GREAT OONES HOLE,MENDIPS
285900	60900	40700	1.146	8	GO1-3	D. FORD UNPUBLISHED
48600	1700	1700	1.135	12	GO2-1TOP	
277000	93000	93000	1.15	7	GO1A	
121000	17000	17000	1.070	8	GO1C	
36700	2200	2200	1.467	82	SC101	ST. CUTHBERTS SWALLET,MENDIPS
81400	6200	6000	1.261	15	2STC6	
90600	10700	10100	1.297	6	2S1C7-1	
29600	1200	1200	0.856	48	2STC7-2	
11500	1400	1400	1.990	5	2STC8	
56800	6000	5900	1.362	5	2STC3T	
71500	13300	12700	1.358	3	2STC3B	
63600	8800	8400	1.192	18	2STC4T	
185200	45900	29500	1.094	27		TOPLESS AVEN,MENDIPS
314400	100000	66400	1.092	43		KAMELI 1980
45150	2110	1900	1.827	8	810818-2A-III	RHINO RIFT,MENDIPS
67100	2000	1980	1.838	17	810818-II	ATKINSON ET AL 1984
74000	4260	4260	1.564	11	810818-I	
58300	2700	2600	1.589	9	810818-2B	
47790	2960	2880	1.914	11	810818-3-III	
47100	1900	1860	1.751	25	810818-3-I	
54000	2200	2200	2.059	67	810818-3-II	
8250	1740	1720	1.226	5	810818-1-III	
9500	700	700	1.294	73	810818-1-IT	
6160	500	400	1.296	30	810818-1-IB	
41400	8000	7900	1.483	11	MOT-1	MANOR FARM,MENDIPS
42000	6700	6600	1.411	7	MOB-1	D. FORD UNPUBLISHED
106900	9900	9300	1.242	16	81SW1	SWILDONS HOLE,MENDIPS
11200	4100	4200	1.576	1	81SW2	
3300	2900	2900	1.424	1	81SW3B	
100600	4300	4200	1.529	52	SWSTP6-9	
99400	9100	8700	1.317	5	SWSTP6-10	
108800	6500	6200	1.345	5	SWSTP7	
7600	1400	1400	1.463	5	SWSTP8	
159700	48200	40000	3.318	5	SWPG4-6	
16300	6000	6000	1.613	8	SW40-1B	
153000	8000	6000	1.390	40	BC2-82-B1A	BLEADON CAVE
225000	18000	15000	1.110	34	BC2-82-C1	P. SMART UNPUBLISHED
110000	14000	11000	1.110	48	BC2-82-A	<10% Th YIELD
14000	9000	9000	1.270	15	GRAVEL POT.YORKS.	ATKINSON ET AL 1978
6000	1000	1000	1.220	999	GP3	
131000	18000	18000	1.330	57	Y1	
61000	4000	4000	1.410	999	Y3:1	

92000	5000	5000	1.490	20	Y3:2	
112000	5000	5000	1.550	92	Y3:3	
12000	1000	1000	0.830	16	Y5	
12000	2000	2000	1.140	33		WHITE SCAR CAVE.YORKS.
13000	7000	7000	1.640	17	WS2	
6000	2000	2000	1.990	45	WS3:2	
90000	11000	11000	2.270	100	WS3:3	
225000	75000	45000	1.290	50	WS5	
14000	7000	7000	2.600	17	WS6:1	
16500	4000	4000	2.02	38	WS6:2	
121000	14000	12000	1.56	16		BELLE HOUGUE.JERSEY. KEEN ET AL 1981
218000	29000	23000	1.018	36		WHITE SCAR CAVE. GASCOYNE ET AL 1983
256000	62000	39000	0.995	21	76106A	
11600	700	700	1.201	7	76108	
6000	300	300	1.082	23	76108-2T	
11100	400	400	1.192	25	76108-3B	
10100	500	500	0.996	25		IBBETH PERIL CAVE I
29400	2200	2200	1.067	15	76111	
13700	1300	1300	0.947	200	76111-2T	
5700	600	600	1.003	13	76111-3B	
7600	700	700	0.960	200	76112	
114000	7000	7000	1.073	110		LANCASTER HOLE.EASE GILL CAVERNS
114000	7000	7000	1.130	129	76121-2B	
91000	5000	5000	1.203	54	76122	
71000	3000	3000	1.386	37	76122-2B	
13300	1000	1000	1.229	13	76124	
9800	500	500	1.330	24	76124-2B	
38000	1000	1000	1.628	105	76125	
39000	2000	2000	1.518	66	76125-4T	
800	100	100	0.719	200	76126	
9700	300	300	0.713	22	76126-2B	
225000	25000	20000	0.878	200	76127	
237000	22000	18000	0.848	200	76127-4	
11500	500	500	0.745	43	76128	
1200	200	200	0.727	3	76128-2	
900	100	100	0.789	3	76129	
11400	600	600	0.749	10	76129-2	
12000	500	500	0.799	31	76129-3	
9600	300	300	1.222	72	76130	
5500	200	200	1.232	153	76130-T2	
9000	300	300	0.760	45	76131	
6500	200	200	0.820	3	76133	
9800	500	500	0.778	200	76133-2	
95000	4000	4000	1.192	52	76135	
86000	3000	3000	1.240	200	76135-2	
140000	10000	11000	1.242	200	77120-A1	
109000	4000	4000	1.161	124	77120-A2	
104000	4000	4000	1.417	200	77120-B2	
87000	4000	4000	1.577	200	77120-B3	
67000	2000	2000	1.577	11	77120-B4	
87000	5000	5000	1.380	4	77120-B5	
66000	5000	5000	1.473	200	77120-B1	
54000	3000	3000	1.425	23	79005-3	
43000	3000	3000	1.429	12	79005-1	
58000	4000	4000	1.198	24	77121-1	
52000	2000	2000	1.314	44	77121-3	
58000	2000	2000	1.518	47	77121-4	
137000	8000	8000	1.178	200	77121-5	
104000	3000	3000	1.373	89	77121-6	

109000	5000	5000	1.313	73	77121-2	
78000	3000	3000	1.284	20	77122B	
35000	1000	1000	1.565	75	77123B	
126000	5000	5000	1.031	160	77126	
106000	4000	4000	1.152	200	77126-2	
199000	21000	17000	1.117	62	79003-A1	
257000	22000	18000	1.178	29	79003-C1	
236000	20000	17000	1.313	200	79120-1	
313000	69000	48000	1.156	69	79120-3	
288000	63000	27000	0.993	178	79120-2	
44000	1000	1000	1.622	103	79121-1	
35000	1000	1000	1.553	200	79121-2	
126000	6000	6000	1.113	200	79121-1	
126000	6000	6000	1.131	200	79124-5	
95000	5000	5000	1.420	49	79124-3	
73000	4000	4000	1.297	200	79124-2	
152000	35000	27000	1.270	6	76140	INGLEBOROUGH CAVE
111000	11000	11000	1.462	10	76141-1	
68000	5000	5000	1.341	19	76141-2	
156000	45000	33000	1.306	14	76142-1	
101000	14000	13000	1.287	8	76142-2	
136000	43000	31000	1.132	4	76142-3	<10% YIELD
186000	41000	30000	1.267	3	76143	
11500	1200	1200	0.952	2	76144	
22200	1200	1200	1.078	3	76144-2	
11900	600	600	0.784	2	76145	
98000	14000	13000	1.480	26	77143-1	
98000	10000	10000	1.392	22	77143-A2	
125000	8000	8000	1.192	41	77143-B1	
115000	8000	8000	1.343	72	77143-B3	
110000	10000	10000	1.337	24	77143-B2	<10% YIELD
219000	45000	32000	1.006	3	76152	VICTORIA CAVE
19000	1600	1600	1.301	4	76153	
180000	16000	14000	1.049	53	76154	
205000	34000	26000	1.152	59	77151-A1	
287000	33000	25000	0.984	26	77151-A2	
281000	43000	31000	1.037	47	77151-B1	
265000	29000	23000	1.059	130	77151-B2	
250000	29000	23000	1.057	128	77151-C4	
188000	13000	11000	1.081	102	77151-C3	
255000	28000	23000	1.112	118	77151-C5	
195000	19000	17000	1.081	56	77151-C1	
191000	9000	9000	1.020	200	77151-C2	
307000	54000	37000	1.104	25	77159-1	
104000	7000	7000	1.114	9	77159-2	
253000	66000	38000	1.138	23	77230-F1	
25500	3600	3600	0.872	3	77230-H1	
243000	27000	21000	0.982	42	77231	
214000	32000	24000	0.947	12	77234	
226000	16000	14000	1.055	200	79150-4	
183000	10000	10000	1.003	200	79150-5	
252000	23000	19000	1.087	66	79151-1	
263000	19000	16000	1.061	84	79151-2	
321000	37000	28000	1.047	47	79151-3	
171000	11000	10000	1.042	52	79153	
181000	14000	13000	1.076	80	79158-1	
185000	10000	10000	1.072	146	79158-3	
173000	9000	9000	1.043	123	79158-2	
102000	11000	11000	1.000	44	79000	<10%,PIGYARD MUSEUM V.C.

120000	7000	7000	1.019	20	79000-2	
104000	6000	6000	1.100	20	79001-1	
126000	9000	9000	1.033	152	79001-2	
135000	8000	8000	1.022	34	79001-3	
131000	9000	9000	1.012	16	79002	
125000	7000	7000	1.057	31	79021	
123000	7000	7000	0.994	71	79023-1	
71000	3000	3000	1.120	111	79025-1	
114000	5000	5000	1.048	84	79025-2	
120000	6000	6000	1.037	47	79025-3	
119000	5000	5000	1.022	200	79026	
128000	12000	12000	1.295	16	76160-2	LOST JOHN'S CAVE
123000	29000	23000	1.283	15	76160-3	<10% YIELD
12100	5500	5500	1.273	1	76161-1	
99000	4000	4000	1.003	178	76164-1	
105000	7000	7000	0.929	200	76164-2	
106000	4000	4000	0.945	200	76164-3	
116000	12000	12000	0.938	111	76165	
92000	4000	4000	0.944	127	77162-1	
101000	3000	3000	0.898	200	77162-4	
96000	3000	3000	0.941	200	77162-6	
96000	3000	3000	0.914	85	77162-9	
126000	5000	5000	0.862	45	77162-8	
109000	5000	5000	0.927	200	77162-10	
112000	3000	3000	0.947	37	77162-7	
113000	5000	5000	0.916	92	77162-3	
14700	600	600	1.398	5	76190	GRAVEL POT.YORKS.
5100	600	600	1.368	5	76190-2	
10100	600	600	1.409	27	76190-3	
13100	1400	1400	1.238	65	76191-1	
10700	500	500	1.235	29	76191-3	
9300	900	900	1.204	13	76191-4	
9600	400	400	1.326	28	76192-2	
7600	400	400	1.279	16	76201-1	GAPING GILL
7000	300	300	1.337	16	76201-3	
44000	1000	1000	1.181	48	76206-1	
114000	8000	8000	1.290	76	76207-1	
135000	16000	14000	1.233	27	76207-2	
1900	200	200	1.512	3	76208-1	
800	200	200	1.580	8	76208-T	
3400	300	300	1.542	6	76208-3	
800	100	100	1.120	6	76209-1	
39000	2000	2000	1.370	99	76210-1	
38000	1000	1000	1.200	122	76210-2	
253000	30000	24000	1.164	28	76211-1	
319000	100000	44000	1.185	20	77209-3	
14600	700	700	1.218	4	76212-2	
12200	400	400	1.274	7	76212-3	
1400	100	100	0.972	3	76215-1	
1300	100	100	1.144	6	76216-1	
289000	24000	20000	1.296	181	77200-1	
10300	300	300	1.337	15	77201-1	
10800	400	400	1.351	55	77201-2	
46000	1000	1000	1.842	95	77205-1	
50000	1000	1000	1.858	29	77205-2	
11000	600	600	1.927	12	77210A-1	
168000	11000	10000	1.123	35	77241-1	KINGSDALE MASTER CAVE
300000	100000	43000	1.015	74	77242-1	
230000	23000	19000	1.053	73	77243-1	

10400	1200	1200	1.680	10	B5Q	KINGSDALE CAVE.LATHAM ET AL 1979
11000	1800	1800	1.700	4	B8Q	
16300	2400	2400	1.700	999	B14Q	
12000	1700	1700	1.770	999	D14Q	
10700	2300	2300	1.610	15	D20Q	
12300	1400	1400	1.610	41	E20Q	
125000	6000	6000	0.993	64	78000	<10%. TREAK CLIFF CAVERN.
131000	4000	4000	1.129	121	78001	FORD ET AL 1983
126000	3000	3000	1.046	999	78002	
186000	7000	7000	1.147	187		WINNATS HEAD CAVE (UPPER SERIES)
191000	15000	13000	1.109	142	78004-3	
176000	8000	7000	1.182	557	78020-2	
9000	2000	2000	1.287	84		<10%. WHINNATS HEAD CAVE (LS)
54000	3000	3000	1.168	151	80039	
96000	4000	4000	1.208	11	80027	SPEEDWELL CAVERNS
17000	1000	1000	1.447	4	80028	
172000	21000	18000	1.057	7	78022	SARAH'S CAVE
24000	1000	1000	1.334	2	78023	MERLIN'S CAVE
5000	1000	1000	0.914	132	78045	PINDALE CAVE
59000	3000	3000	1.290	43	79006-1	PEAK CAVERN
51000	2000	2000	1.473	73	79007	
73000	2000	2000	1.240	24	79008	
51000	2000	2000	1.447	999	79009	
1100	100	100	1.143	59	80031	
3400	100	100	1.099	144	80029	GIANT'S HOLE
17000	2000	2000	1.035	52	80030	<10% YIELD
54000	2000	2000	1.262	185	80033	
48000	1000	1000	1.242	617	80034	
125000	22000	19000	1.145	8	80037	
3600	200	200	1.075	12	80041	
2200	200	200	1.013	41	80043	
102000	6000	6000	1.123	9	80035	THIRST HOUSE CAVE
195000	14000	13000	1.121	17	80042	HOLE-IN-THE-WALL
145000	17000	14000	1.112	10	80056	WATER ICICLE CLOSE MINE
225000	64000	41000	1.082	13	80057-2T	
122000	12000	12000	1.520	200		UAMH AN CLAONAITE,SUTHERLAND,SCOTLAND
30000	4000	4000	2.320	31		ATKINSON ET AL 1986.
26000	3000	3000	1.290	30		FIREHOUSE CAVE,SUTHERLAND
9000	2000	2000	1.130	200		
12000	1000	1000	1.290	7		UAMH AN TARTAIR,STHERLAND
2000	1000	1000	1.040	200		TREE HOLE CAVE,SUTHERLAND
5000	1000	1000	1.190	200		UAMH AN TARTAIR,SUTHERLAND
7000	1000	1000	1.160	200		
9000	1000	1000	1.100	200		
5500	800	800	1.250	200		
11000	2000	2000	1.320	17		UAMH CALLIDIE PERAIG,SUTHERLAND
35000	1500	1500	0.98			KINGSDALE MASTER CAVE,YORKS.
6600	200	600	1.052			SIMONS POT,YORKS.
82000	8000	8000	1.290	14		STUMP CROSS,SUTCLIFFE ET AL 1984
84000	8000	8000	1.180	17	SURRC 535	
83000	6000	6000	1.440	95	HAR 2663	
81000	5000	5000	1.870	72	HAR 2635	
84000	5000	5000	1.350	23	SURCC 516	
72000	6000	6000	1.330	7	HAR 2673	
109000	10000	9000	1.380	7	HAR 2675	
42000	6000	6000	1.330	9	HAR 2662	
57000	10000	10000	1.240	14	HAR 2670	
93000	14000	14000	1.310	50	HAR 2657	
116000	9000	9000	1.200	24	SURCC 533	

160000	18000	14000	1.420	47	SURCC 539	
15000	1000	1000	1.300	200	SURCC 502	
17000	2000	2000	1.210	12	SURCC 517	
39000	4000	4000	1.070	200	SURCC 512	
44000	4000	4000	1.210	28	HAR 2654	
29000	2000	2000	1.320	45	HAR 2658	
38000	3000	3000	1.400	213	HAR 2659	
47000	2000	2000	2.080	318	HAR 2660	
45000	4000	4000	1.150	999	HAR 2655	
60000	7000	7000	2.100	18	HAR 2656	
58000	4000	4000	1.790	166	HAR 2661	
60000	4000	4000	2.780	65	HAR 546	
90000	8000	8000	1.680	135	HAR 2652	
108000	18000	18000	1.930	37	SURCC 515	
110000	14000	12000	1.610	116	SURCC 549	
118000	12000	12000	2.010	123	SURCC 514	
176000	29000	20000	1.390	68	SURCC 539	
176000	8000	8000	1.640	777	HAR 2671	
172000	7000	7000	1.650	754	HAR 2672	
238000	46000	34000	1.530	29	SURCC 548	
222000	46000	37000	1.420	45	SURCC 547	
171000	28000	24000	2.160	12		MARSWORTH TRAVERTINE,GREEN ET AL 1984
165000	34000	27000	1.480	15	HUTH 2215	
149000	16000	14000	1.550	37	HUTH 2237	
307000	44000	35000	1.137	999		PONTNEWYDD.SCHWARCZ IN GREEN 1984
179000	12000	12000	1.085	170	B262	
123000	4000	4000	3.879	999	B275	
227000	24000	20000	1.140	39	B279	
217000	24000	20000	1.092	11	B274	
209000	16000	16000	1.001	78	B148	
149000	9000	9000	1.039	85	HPS-78850	
130000	7000	7000	1.066	50	HPS-78851	
204000	20000	20000	1.047	70	BOb:2	
255000	89000	47000	0.930	52	B162	
177000	12000	12000	1.146	9	CO	
125000	6000	6000	1.312	87	D187	
83000	9000	9000	1.151	7	D642	
227000	13000	13000	1.282	86	D534:2	
300000	54000	37000	1.044	23	D534:3	
89300	2700	2700	1.384	79	D321:T	
95700	4300	4300	1.401	38	D321:B	
161000	11000	11000	1.151	62	D604	
196000	27000	22000	1.233	114	D1288B:03	
257000	60000	40000	1.254	76	D1288B:02	
193000	21000	18000	1.374	35	D1288B:01	
184000	26000	22000	1.300	51		IVANOVICH ET AL IN GREEN 1984
285000	71000	45000	1.320	715	HAR 5612	
205000	35000	27000	1.280	999	HAR 5624	
262000	69000	44000	1.290	101	HAR 2256	
238000	44000	33000	1.440	88	HAR 5610	
218000	39000	29000	1.280	422	HAR 5622	
188000	25000	21000	1.400	244	HAR 5623	
239000	41000	31000	1.430	129	HAR 2257	
229000	41000	32000	1.360	217	HAR 5609	
218000	42000	31000	1.390	320	HAR 5621	
13000	7000	5000	1.080	3	D188:1	DEBENHAM IN GREEN 1984
32000	12000	11000	0.970	5	D188:2	
15000	7000	7000	1.110	4	D188:3	
160000	22000	18000	1.130	39	D292:1	

185000	45000	31000	1.180	20	D292:2	
302000	100000	74000	1.270	33	D1711	
176000	29000	23000	1.200	73	D1693	
174000	36000	27000	1.310	44	D471:2	
104000	14000	12000	1.060	27	B111:1	
143000	20000	17000	1.090	27	B111:2	
244000	88000	46000	1.110	36	BOB:2	
236000	80000	46000	1.110	20	BOB:1	
118000	17000	15000	1.010	26	B396	
106000	15000	13000	1.060	19	B396:2	
243000	91000	47000	1.170	68	B409	
357000	100000	61000	1.100	28	KC3-83-B1	KENT'S CAVERN
243000	85000	46000	1.090	64	KC3-83-B2	P. SMART UNPUBLISHED
99500	9500	8500	1.350	28	KC4-83-C1	
210000	87000	55000	1.080	33	KC2-83-B1	
8300	800	700	1.570	62	BM-1975-A1	BACON HOLE
7900	300	300	1.520	52	BM-1975-B	
4600	2900	2900	1.370	3	1977-103:2	SCHWARCZ IN BOWEN ET AL 1984
13000	3000	3000	1.500	16	1978-801:01	
12800	1700	1700	1.520	4	1978-801:02	
12000	10000	10000	1.270	2	1980-'STAL 1'	
62000	42000	37000	1.240	2	1982-253	
81000	18000	18000	1.490	999	1981-250	
129000	16000	16000	1.350	47	1981-212:01	
125000	26000	26000	1.610	8	1981-212:02	
129000	30000	30000	1.480	8	1981-212:03	
116000	18000	18000	1.910	9	1981-252:02	
122000	11000	11000	1.340	31	1981-252:01	
175000	19000	19000	1.490	48	1980-'STAL 2'	
107000	10000	10000	1.320	39	MH1-84-A	MICHIN HOLE
25000	1500	1500	1.400	4	MH1-82A	P. SMART UNPUBLISHED
46000	3500	3400	1.400	5	MH1-82B	
37000	4000	3500	2.160	12	MH1-82C	
68000	5000	3500	1.530	16	MH1-82D	
96600	9400	8700	1.260	44	MH1-84B	
302000	162000	60000	1.000	36	MH1-84C	
6100	700	700	1.660	2	MH3-82A	
3600	400	300	1.690	2	MH3-82B	
170000	20000	17000	1.280	8	MH3-400B	
108000	16000	14000	1.340	177	MH3-400A2	
88800	11100	9700	1.100	12	MH5-82A1	
101000	16000	16000	1.465	19	78MH6:1	SCHWARCZ IN BOWEN ET AL 1984
130000	25000	25000	1.323	10	78MH6:2	
107000	10000	10000	1.364	33	81824-1	
197000	70000	50000	1.274	9	81824-2	
127000	21000	21000	1.410	14	81824-3	
180000	29000	17000	1.050	3	OFD-A3(B)	OFD,WALES,<10%Th YIELD
108000	5000	5000	1.06	41	OFD-A4	NOEL CHRISTOPHER UNPUBLISHED
5000	600	500	1.05	2	OFD-A5	
114000	3000	2000	1.290	8	OFD-A7	
13900	300	200	0.900	28	OFD-A8	
88000	2800	2800	1.050	11	OFD-TE3A(B)	
117000	8000	7000	1.370	46	OFD-TE6(T)	<10% U YIELD
282000	20000	17000	1.040	85	OFD-TE7	
120000	11000	10000	1.350		OFD-TE10	<10% Th YIELD
116000	6000	5000	1.400	32	OFD-TE6(B)	
5700	100	100	0.960	76	OFD-TE8	
84000	3200	3000	1.390	81	OFD-TE16(B)	<10% Th YIELD
9700	200	200	1.090	45	OFD-TE15(B)	

92000	3000	2900	1.260	97	OFD-TE17(T)	
127000	9000	7000	1.410	25	OFD-TE12(M)	
89400	3000	2900	1.090	61	OFD-TE16(T)	
14500	600	700	1.110	9	OFD-LE3	
9900	600	500	0.97	6	OFD-LE6	
81500	3400	3300	1.230	88	OFD-WFS1	
106000	2000	2000	1.030	132	OFD-WFS2	
6600	200	200	0.870	17	PWC-1A	POWELLS CAVE,WALES.
111000	18000	17400	1.300		DYO-1B	<10%TH,DAN-Y-OGOF,WALES.
3400	300	200	1.070	3	DYO-B9(B)	
4700	300	200	1.070	10	DYO-B8	
9700	300	300	1.310	47	DYO-B6	
76300	1500	1400	1.560	27	DYO-B7	
105000	1000	2000	1.090	78	DYO-6	
900	40	40	1.230	4	DYO-2	
117000	5000	4000	1.040		BC-1	OGOF-Y-ESGRYN,WALES.
165000	8700	8100	1.106	131	820324-6	ROBIN HOOD'S CAVE,CRESWELL
165700	8500	7900	1.134	156	820324-6	ROWE 1987.
180500	13000	11700	1.165	49	811205-1	
135200	8900	8200	1.022	20	820324-9	
109900	7400	7000	1.104	20	820324-9	
101000	5600	5500	1.136	17	820324-12	
84000	5600	5600	1.271	8	820324-11	
10500	900	900	1.280	7	820324-10	
10300	300	300	1.415	27	820324-14	
12600	500	500	1.255	25	820324-14	
13700	800	900	1.612	21	820324-17	
12500	500	500	1.721	400	830810-1	
8900	400	400	1.712	14	820324-16	
140600	8000	7400	1.077	146	831024-1	
126000	7300	6900	1.132	151	840227-4	
8100	1600	1600	1.147	999	830809-1	CAVE C7,CRESWELL.
211300	15400	13500	1.072	299	830809-3	
8700	600	600	1.103	4	830809-9	
7600	1100	1100	1.197	32	830809-6	
101900	5200	5000	1.149	62	830809-4	
186300	13700	12200	1.160	182	830809-2	
288600	49500	34300	1.073	147	840228-3	
13600	1000	1000	1.150	12	840228-4	
208100	16100	14200	1.215	77	830809-10	
238900	27800	22400	1.094	31	840228-1	
270800	40700	30000	1.104	70	840228-2	
219000	21000	17800	1.182	14	830809-5	
298000	61700	40600	1.095	113	840605-4	
147300	9300	8600	1.196	124	840605-5	
113100	7300	6800	1.103	21	840606-4	
270700	47600	33400	1.074	66	840525-1	
125500	6700	6300	1.140	12	840606-1	
194900	13800	12300	1.119	8	840605-3	
276400	42100	30700	1.089	12	840605-1	
228800	21200	17800	1.098	14	840605-2	
14700	600	600	1.327	30	840322-1	PIN HOLE,CRESWELL.
103700	4900	4700	1.209	164	830810-2	CAVE C8,CRESWELL.
184200	14000	12600	1.489	4	831027-6	ELDERBUSH,MANIFOLD VALLEY
184000	11300	10400	1.501	17	831027-7	
208900	21800	18500	1.384	5	840524-1	
23200	2300	2200	1.204	2	831027-4	THORS CAVE.
132000	9100	8400	1.251	84	831028-4	LYNX CAVE.
283700	34000	26800	1.305	18	840921-5	DARFUR RIDGE.

ADDRESSES OF AUTHORS OF UNPUBLISHED UK SPELEOTHEM URANIUM SERIES DATES QUOTED IN APPENDIX VII.

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